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Original scientific paper

ANALYSIS OF ADDITIVE MANUFACTURING TECHNOLOGY INPUT PARAMETERS IN MANUFACTURING OF BOLUS

Kaltrine Jakupi[1,2]**, Vladimir Dukovski**[1]**, Atanas Kočov**[1]

[1]*Faculty of Mechanical Engineering, Ss. Cyril and Methodius University in Skopje, P.O. Box 464, MK-1001Skopje, Republic of North Macedonia*
[2] *"Hasan Prishtina" University in Prishtina, Faculty of Mechanical Engineering, Prishtina, Kosovo*
vladimir.dukovski@mf.edu.mk

A b s t r a c t: This paper presents the design and production of bolus with additive manufacturing technology for a specific patient in routine radiation therapy. The patient face was simulated with the Computer Tomography (CT) and then the bolus was designed with Computer Aid Designed (CAD) software, 3D Slicer. The bolus was segmented for radiotherapy needs but the head was also segmented only for illustration reasons. For slicing of 3D models were used PrusaSlicer software. All inputs parameters of printing were chosen by the quality of printing and the purpose of use. The 'G-code' was created for printing. The printing is done with the Fused Deposition Modeling (FDM) additive manufacturing and Polylactic Acid (PLA). The printer was calibrated and used in accordance with the producer manual. This technique shows many advantages like the precision of model printing, short production time, cheap production, and higher dosimetric benefits for dose distribution of the patient.

Key words: additive technology; design; manufacturing; bolus

АНАЛИЗА НА ВЛЕЗНИТЕ ПАРАМЕТРИ ПРИ ИЗРАБОТКАТА НА БОЛУС СО АДИТИВНА ТЕХНОЛОГИЈА

А п с т р а к т: Во трудот се опишани истражувањата за конструирањето и изработката на болус со помош на адитивна технологија за определен пациент врз кој се реализира рутинска терапија со радијација. Обликот на лицето на пациентот е моделиран со компјутерска томографија (CT), а потоа болусот е дизајниран со компјутерска поддршка на софтверотCAD, 3D Slicer. Болусот е сегментиран заради терапијата додека главата е сегментирана заради илустрација на постапката. За генерирање на пресеците на 3D моделот е користен софтверот PrusaSlicer. Сите влезни параметри се избрани со цел постигнување соодветен квалитет на печатењето и соодветни потреби на терапијата. Како влез за печатарот е генериран соодветен G-код. Печатењето е реализирано со постапката Fused Deposition Modeling (FDM) на адитивно производство со користење на материјалот polylactic acid (PLA). Печатачот е калибриран и користен согласно упатството на производителот. Оваа техника покажа многу предности: прецизност на изготвениот модел, кусо време на изработка, евтино производство и големи придобивки во дистрибуцијата на радијацијата при рутинската терапија.

Клучни зборови: адитивна техноилогија; дизајн; изработка на болус.

1. INTRODUCTION

Additive Manufacturing (AM) terminology is used for technologies that successively join material to create physical objects, usually layer by layer, as specified by 3D model data, previously designed as a digital file. Additive manufacturing is known also as 3D printing or rapid production (RP), it is based upon similar data pre-processing operations converting the virtual 3D models, created using computer-aided design or 3D scanning. Over the past three decades, several rapid prototyping techniques that involve the processing of material in solid, powder, or liquid form have been developed.

The application of AM technologies in a different field is growing every day. This technique is applied in various applications and specifically in the engineering industry, medicine, education, architecture, toys, and entertainment.

Many researchers proved that AM techniques are comfortable for different industry branches like automotive, aviation, constructions, etc. In addition, there has recently been a rapidly increasing trend of AM techniques in various fields of medicine, like biomodelling for surgery [1], implants [2], boluses [3], and other important applications in medicine [4–6].

In this paper, is discuss in detail the additive manufacturing process to create a device for medical application in routine radiotherapy practice, called a bolus. The process itself is made by many steps, each of them has a great impact on the quality of the final product. The focus of this study is to create the end-use bolus that can be used during the radiotherapy treatments to provide the exact dose of X-rays to planning tumor volume (PTV) and to protect the healthy tissue. The process of production must have a precise 3D printing technique, to be cost-efficient and relatively short time to be produced.

2. DESIGN AND MANUFACTURING OF 3D PRINTED PARTS

In general, in the clinical routine, common process for external beam radiotherapy (EBRT) consists of five main steps: 1) immobilization of patient, 2) simulation – usually by computer tomography (CT), magnetic resonance (MRI), or other imaging techniques, 3) contouring – segmentations of tumor and organs, 4) planimetry of radiation by computerized treatment planning system (TPS), which simulates the radiotherapy process where dose beam directions and intensities are optimized for enhanced patient treatment by choosing beam number, shape, directions, and dose contribution, 5) treatment of the patient – the total dose will be given to the patient in small fractions as it was planned by previous steps.

Each bolus is unique and made for a specific region of the patient which is possible due to the CT simulation of the patient. During this procedure, the patient image is created by the interaction of X-rays with the patient body and a digital image with the exact shape of a bolus.

Those clinical steps are linked directly to the design and manufacturing of a 3D bolus. This process is presented in Figure 1. For the first step a CT simulator is used, Siemens Somatom, with standard protocol and with slides thickness 5 mm.

The DICOM file generated by the imaging step was used for segmentation, presented as the second step. Therefore, to get a 3D image of a bolus it is required to use special software to convert the DICOM data into files that a 3D printer can "read".

For design models usually Computer-Aided Design (CAD) plays a crucial role, and for segmentation software Slicer ver.4.11 software [7] was used. It is a well-known open-source software package used widely for segmentation in medicine. The segmentation editor module of 3D Slicer software gives the possibility to delineate a structure of interest; it can be a specific organ or additional part of the patient, as a bolus. The second step included patient head segmentation and bolus design for the interested region. Figure 2 presents the patient DICOM file with red color bolus on the frontal side of the patient's head.

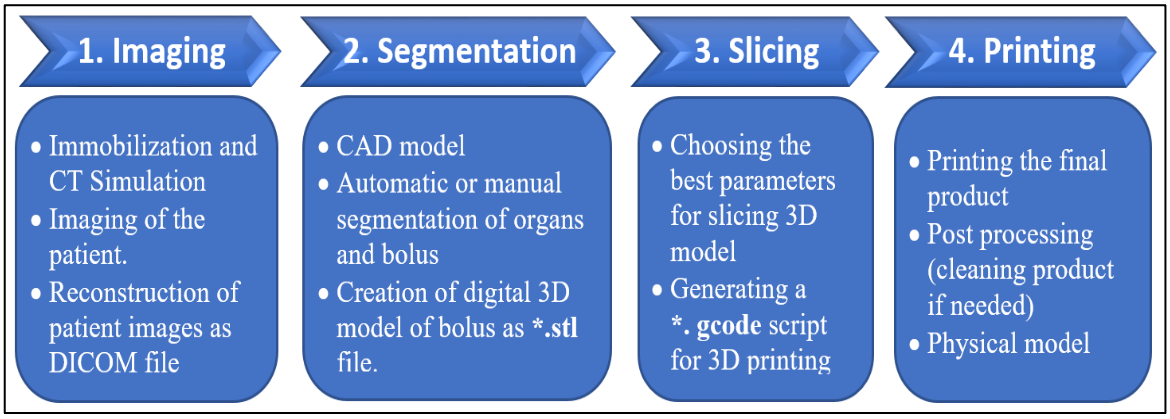

Fig. 1. Scheme of design and production of 3D printed bolus

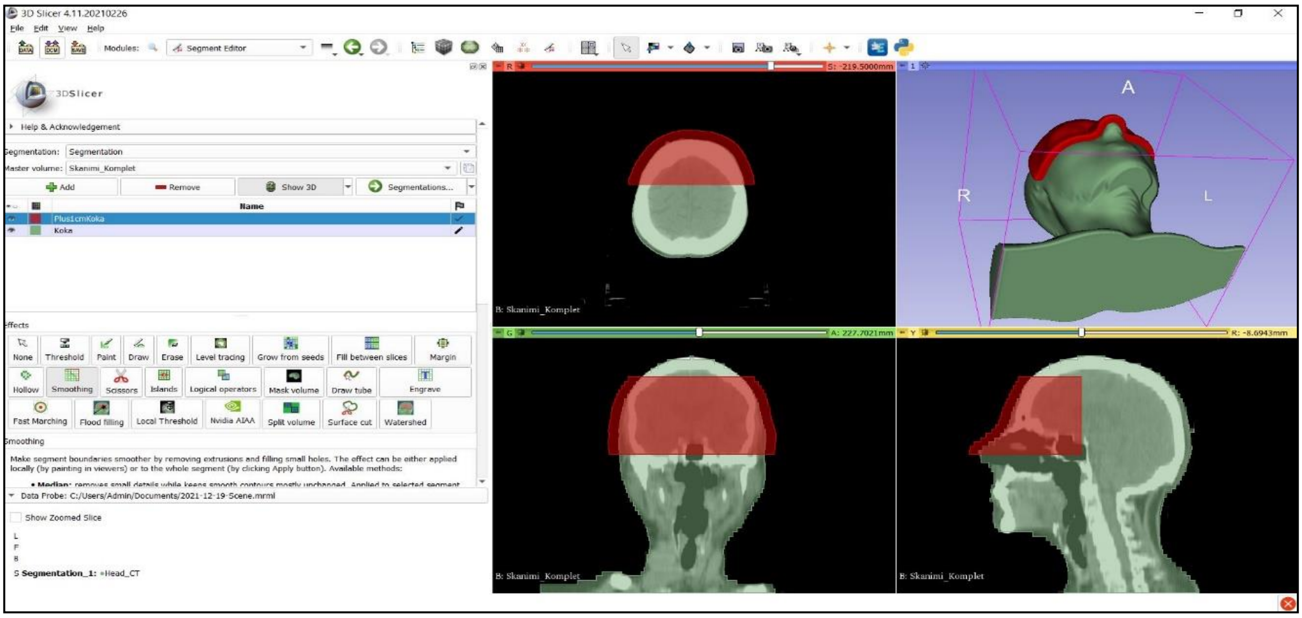

Fig. 2. 3D slicer with main steps up to *STL file

The segmentation process has two steps: contouring of the patient's skin and the bolus. With the Level Tracer button, from the Segment Editor Module of 3D Slicer, was selected the uniform intensity region of each 2D slice. The background voxel was used to find the closed path that follows the same intensity value back to the starting point within the current slice. Then the Gaussian smoothing tool was applied with a deviation standard of 3 mm to all segments for removing extrusions and filling small holes. After that, the file was exported as a '3D_head.stl' file.

The third step is done by slicing software. Slicer is a 3D printing software program that converts digital 3D versions of an object in printing commands for 3D printer [8]. The Slicer cuts CAD design into horizontal layers based on the selected settings and also computes how much material the printer will required to print the object as well as how long it will take to do it.

In this research PrusaSlicer ver.2.4 was used (Figure 3). The PrusaSlicer (formerly known as Slic3r Prusa Edition or Slicer PE) is a slicer software developed on the basis of the open-source project Slicer. PrusaSlicer is an open-source, feature-rich, frequently updated tool [9] and it can be used also with other 3D printers but in this case it is linked with Original Prusa i3 MK3S+ printer.

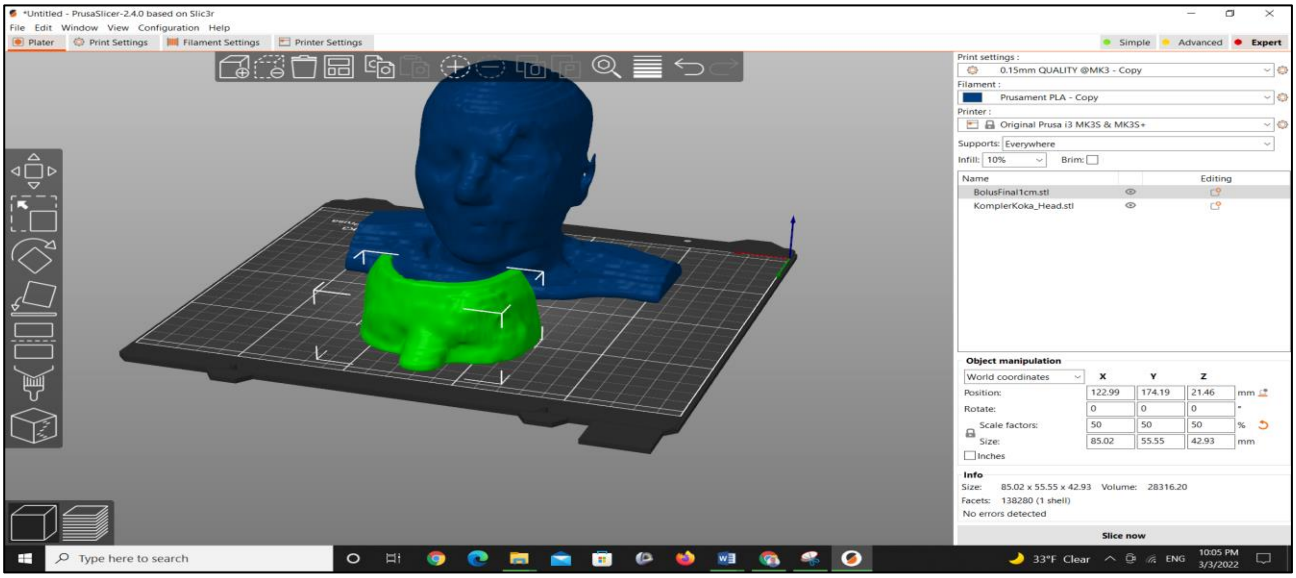

Fig. 3. The Window of PrusaSlicer software

The final step, printing, is realized by printing a thermoplastic material with 3D printer Prusa i3 MK3S+. It is calibrated according to the producer protocols for XYZ axes and for the first layer. The used printer was equipped with an extruder nozzle diameter of 0.4 mm.

Material used in this research was Polylactic Acid (PLA), a biodegradable thermoplastic produced from corn starch and sugar cane. PLA is environmentally friendly, safe to use and it is now the most recommended material for 3D printers [8]. PLA has high mechanical strength and also good other properties [8, 10, 11], and is expected to expand its potential applications.

2.1. *Printing parameters*

Slicer settings do influence the quality of print so it's vital to have the appropriate software program and also setups to get the most effective high-quality print.

The independent input parameters are crucial for creating a bolus with high quality. The parts were printed with PLA filament of the diameter of 1.75 mm and machine nozzle size of 0.4 mm. The manufacturing temperature of PLA can be up to 220ºC, and the print bed temperature usually is 50ºC. The PruaSlicer software offered three different levels of application, a simple level – for beginners with basic input parameters, advanced levels – with a specific option, and the expert level which has available all options, and the user is free to set up each parameter.

The final file created by PrusaSlicer was 'G-code' type. It contains all information for printing the designed model.

2.1.1. *The layer height*

The layer height is the most important input parameter for printing parts with desirable quality. Prints made with thinner layers will certainly develop much more detailed prints with a smoother surface area where it is tough to see the specific filament layers. The thinner layers will take more time to create because the number of layers will increase.

The software and printer used in this research can print by default five different layers high: ultra-detail, detail, quality, speed, and draft with layer high: 0.05, 0.1, 0.15, 0.2, and 0.3 mm, respectively. Otherwise, the printer can print the layer height from 0.01 up to 0.4 mm, the maximum value of layer height corresponds to the extruder nozzle diameter.

To create solid couture of workpieces, the first layer parameter can have different values than other layers described in previous paragraphs. Also, the first layer settings will affect how the model adheres to the print bed.

2.1.2. *The shell thickness*

The shell thickness describes the number of times the external walls of the layout are mapped by the 3D printer to areas of the design. The shell thickness can be vertical or horizontal. The PrusaSlicer has the same parameter with the name 'horizontal shells'. So, this option sets the number of perimeters to generate for each layer. The PursaSlicer may increase this number automatically when it detects sloping surface which benefits from a higher number of perimeters if the extra perimeters option is enabled. This situation is presented in Figure 4 for two different external sloping surfaces.

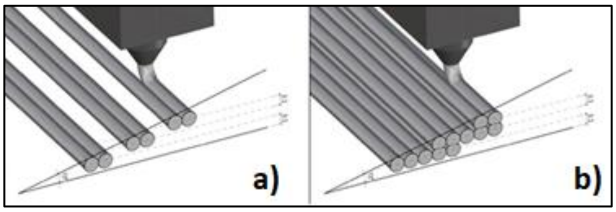

Fig. 4. The shell thickness for
a) high slope surface and **b)** for low slope surface

In this case, an error usually occurs. The defect consists of horizontal contours that are elapsing by a larger distance than the layers are printed in the vertical direction (thread diameter/slice thinness). The shell thickness has the same meaning if it is vertical.

2.1.3. *Retraction*

If the retraction is not set up correctly, the printed workpiece can have oozing problems and it is related to extruder settings. It will happen when the nozzle of a 3D printer has to move across a gap without printing anything. When being consistently extruded, the filament melts enough to be printed. If the printing has a retraction defect, it should be set up to the filament to be pulled back into the nozzle when it is not printing. Once the extruder moves to the next location the printing process continues – the filament is pushed back out and it starts extruding from the nozzle again.

This parameter can be set in advanced with expert levels of PrusaSlicer software. Usually, the retraction effect will be reduced by reducing the temperature of the filament, the steeps with 10ºC should apply and testing till no retraction will be seen.

2.1.4. *Fill density*

The fill density or infill parameter can get costly as well as time-consuming if you're printing with 100% infill. So, a higher infill percentage means much more filaments and time will consume. In PursaSlicer software this parameter is 20 % by default.

To create the patient head and bolus (those pars are shown in Figure 5), infilling parameters were 20 and 90 % at interesting regions. For the head, the intention was only to have it for comparison and the main focus was the bolus.

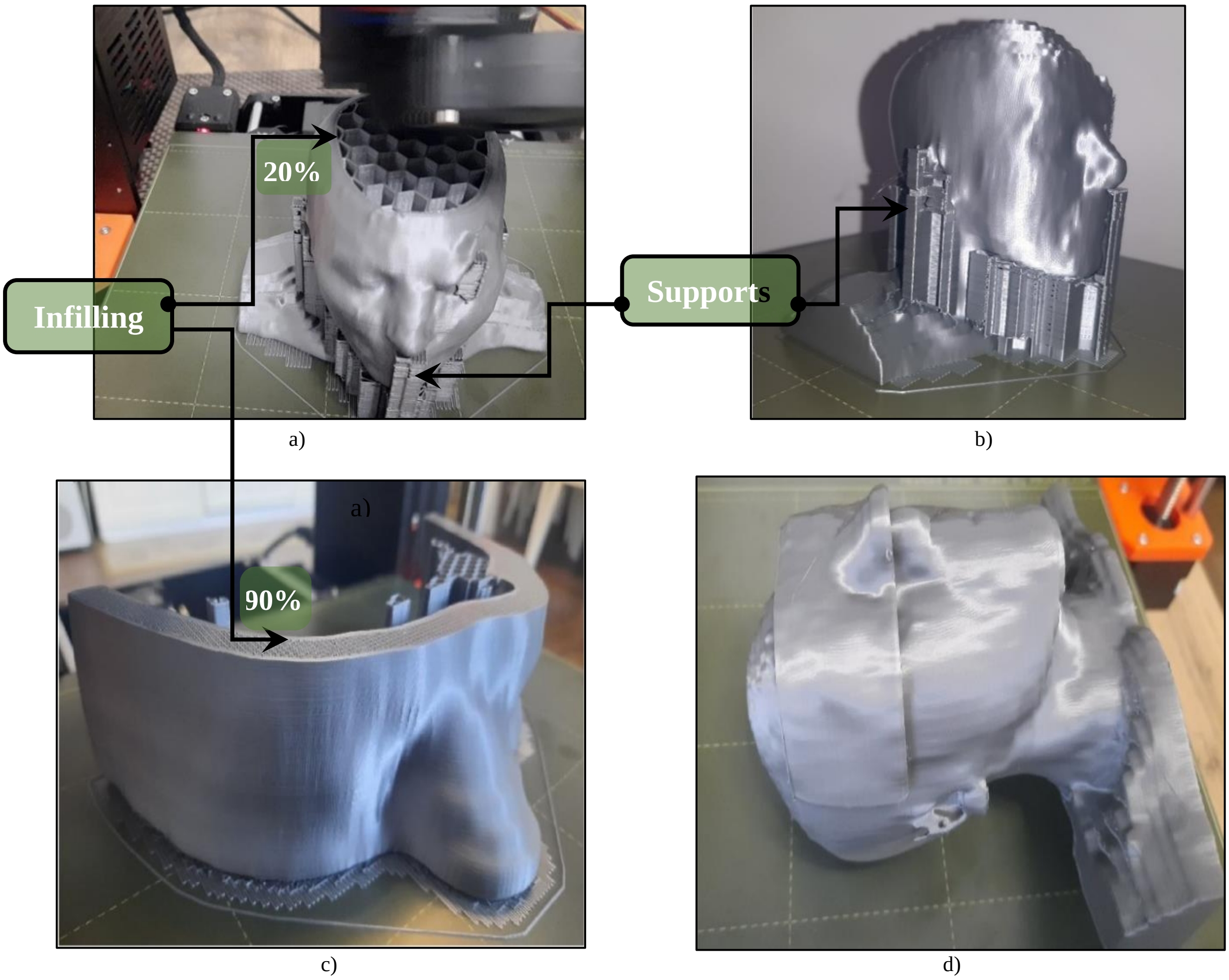

Fig. 5. The final printed workpieces **a)** the head during the printing, **b)** the printed head with supports, **c)** the bolus during printing and **d)** the bolus on the head as it will be used during the treatment of the patient

2.1.5. *Print Speed*

Printing speed refers to the rate at which the extruder travels while it sets filament. Ideal settings rely on what layout you're printing, the filament you're using, the printer, and also your layer Elevation.

A great starting point that PursaSlicer advises is 80 mm/s. There are 15 and 8 speed parameters for advanced and expert mode. Each of the parameters tunes the sped for one element, like infilling, bridges, perimeters, the first layer, support material, etc.

2.1.6. *Supports*

The supports are the printed structures that hold up overhangs of prints, and they're necessary because a printer can't print in air. Ideally, support structures should hold up any "floating" features of a print without adhering too much to the print's surface; otherwise, they can be hard to remove and even damage the appearance of the print.

In a majority of slicers, the most basic support setting is whether to activate them at all. As the rule, if the angle of the next slice is 45ºC and more, the supports must be activated.

2.2. *Information for time and cost*

In general, the process of 3D printing of prototypes reduced the time and cost, compared to the traditional methods [12].

In this research, only the head and the bolus are printed and no other technique is applied for more detailed comparisons, but as Mohit, A. [13] noticed many factors should be taken into account for the time and cost analyses. These include labor rate, printer cost, design time, programming time, post-processing time and cost, printing cost and time, error and training, etc.

The software PrusaSlicer, under the Filament Settings tab, can add all filament details like diameter, density and cost to calculate how much time and cost will require to print the part.

3. CONCLUSIONS

The main topic of this research was the design and production of bolus parts used for treating the patient by high-energy x-ray photons on radiotherapy practices. The designed products were produced with open-source software 3DSlicer and PrusaSlicer. The products were printed with Original Prusa i3MK3S+ and made of PLA thermoplastic.

The bolus, as the final product, fills all criteria to be used for patient treatment in radiotherapy. The printed bolus was personalized to the patient and offered better dose distribution due to the high precision of production. Also, the production time is very short and the precision of the bolus shape is very important for treatment quality.

Based on the finding of this research, the radiotherapy departments should adopt additive manufacturing techniques in their daily activities due to the benefits previously mentioned. In addition, the staff can easily understand and use this technique due to friendly software.

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