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Use of 3D-Printers to Create Intensity-Modulated Radiotherapy Compensator Blocks*

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Abstract— **Intensity-Modulated Radiotherapy (IMRT) is an important tool for cancer treatment. It concentrates high radiation doses in complex target volumes, while sparing the surrounding tissues. IMRT is traditionally performed using Multileaf Collimators (MLC) or Compensator Blocks. The conventional way used to manufacture IMRT compensator blocks, which uses milling machines, is an important drawback over the MLC method, due to high operational and production costs. In this research, we developed a simpler alternative method to manufacture an IMRT compensator block from a fluency map generated by a commercial treatment planning system (TPS). This map was converted into a mold, and then printed using a 3D printer. The final IMRT compensator block was achieved by filling the mold with cerrobend alloy. To validate this method a quality assurance was performed using dosimetric films to compare the measured dose distributions to those predicted by the TPS system. This comparison showed a good agreement among 8 dose profiles from each situation, with a maximum RMS error of 8.84 % for the tested profiles. This suggests that the 3D printers can be effectively used to manufacture IMRT compensator blocks. The main advantage to this approach is that it can be fully conducted inside a radiotherapy facility, which results in lower costs and production times.**

I. INTRODUCTION

Intensity-Modulated Radiotherapy (IMRT) enables the delivery of high radiation doses to complex target volumes by sparing the surrounding tissues. IMRT provides heterogeneous dose distributions (high dose gradients) that conforms the tumor. This important tool for cancer treatments modifies photons fluency by using some device in linear accelerators. Thereby, IMRT requires significant investments for treatment planning, Quality Assurance (QA) and delivery, which are not always feasible due to budgetary constraints [1].

There are two basic techniques for modulating the intensity of photons beams: (1) Multileaf Collimators (MLC), and (2) Compensator blocks. The first one uses some extra beams collimators (leaves) that automatically move during the radiation exposure. The second one uses some irregular blocks between the radiation source and the patient, in order to modify the photons fluency in a desired manner. The MLC method is more commonly used due to its feasibility. However, both methods use solutions, respectively for MLC movement and block shape, from a treatment planning system (TPS) [2]

Chang, S. X. et al. [3] assessed the benefits and disadvantages of using IMRT compensators blocks. Chang considers that the static nature of compensator blocks simplifies the treatment delivery, dose computation, and QA procedures. Moreover, IMRT compensator blocks can perform continuously varying intensity modulation. MLC has a discrete possibility of modulation at the perpendicular direction of leaves movement (each leaf has a constant width and can move only in one direction). On the other hand, the lack of automation represents a drawback, as the radiation therapists must go into the treatment room to change the compensator blocks (a typical IMRT treatment requires 5-7 blocks). Besides, most used materials make the blocks depend on complex milling machines. With this approach, the blocks need to be manufactured outside the hospital, increasing the time and cost of IMRT blocks.

In this paper, we describe a simpler manufacturing procedure for IMRT compensator blocks which does not require milling machines, and which is based on converting the fluency map into the coordinates describing a mold to be generated by 3D printers. The final block is then produced using this mold and a specific alloy.

In last years, 3D printers have been increasingly used to generate physical objects from designs developed with the aid of digital computers [4]. They use powder and/or plastic materials to create solid structures. There are many types of 3D printers used in several areas such as industry, architecture, odontology and others [5]. Recent 3D printer projects substantially reduced the cost of this technology [6]. However, this prototype machine is not yet inserted yet in the radiotherapy routine. Some physical properties of the materials used in 3D printers, such as the maximum bearable temperature (up to 100 °C), and the resolution of the final printed objects (around 0.2 mm) suggest that this equipment can be alternatively used in radiotherapy procedures.

We then develop and implement an alternative way to create IMRT compensator blocks from IMRT plans using a 3D printer. We intend to attain a manufacturing procedure of cerrobend IMRT blocks that results in lower costs and production times, compared to milling machines traditionally

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needed for this type of alloy. Additionally, the proposed method has the advantage of being fully conducted inside a radiotherapy facility. At the same time, the generated blocks must achieve the same QA criteria used in conventional IMRT blocks for radiation dose distribution [7].

II. MATERIALS AND METHODS

We developed a systematic method for creating an IMRT compensator block from a fluency map generated using a commercial treatment planning system (TPS). This map was converted into mold thickness values, and printed using a 3D printer. The final IMRT compensator block was created by filling the mold with cerrobend alloy. To validate this method a QA was performed using dosimetric films to compare the measured dose distributions to those computed by the TPS. All these steps are described below.

A. *IMRT treatment planning*

The patient's IMRT treatment starts with the planning (treatment virtual simulation) using a TPS. We selected a computed tomography of prostate cancer from our clinical database. A standard setup with seven beam angles directions was used to reach the target. The plan was performed for a Siemens linear accelerator, model Primus, with 6 MeV photons beams energy. The IMRT fluency maps (one for each beam angle) from this prostate cancer plan were generated using Jaws-Only Direct Aperture (JODAO) IMRT algorithm in the PROWESS Panther TPS, version 5. We choose 18 segments per beam angle (mandatory parameter in JODAO IMRT). This high number provides an excellent treatment plan, and a complex intensity map (Fig. 1). Consequently, the treatment time becomes longer (more than 30 min) in such way that is not practicable in a regular radiotherapy facility routine using the conventional delivery IMRT method. This is convenient to our experiment, as we aim at evaluating the proposed methodology's feasibility when dealing with complex plans. In fact, up to 9 segments per beam angle are generally used for a typical prostate cancer plan. However, by using this complex map, we can test our method for an extreme situation as described hereafter.

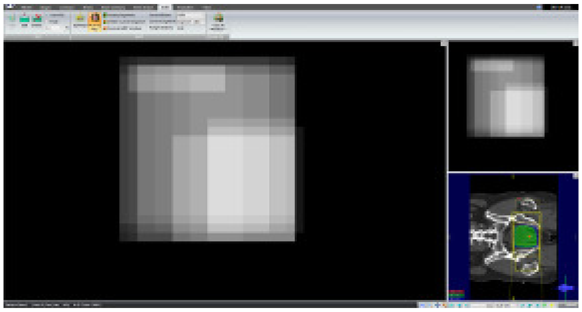

Figure 1. Fluency map generated in a TPS. Darker regions represent lower dose.

B. *Converting fluency maps into mold thickness*

The most heterogeneous intensity map was chosen to create an IMRT compensator block. The fluency map of this beam angle was exported into an RGB image format (Fig. 1) from PROWESS TPS, and converted into a 16 bits gray level map. Then, we transformed this pixels information into mold thickness values (Fig. 2), taking into account the cerrobend dosimetric properties. Cerrobend is an alloy (lead, tin, bismuth, and cadmium) commonly used in radiotherapy, given its low melting point and high density. This alloy has a Half Value Layer (HVL) for 6 MeV photons beams energy around 25 mm. Cerrobend was chosen to fill the mold, and generate the final IMRT block compensator, because it is largely available in radiotherapy facilities.

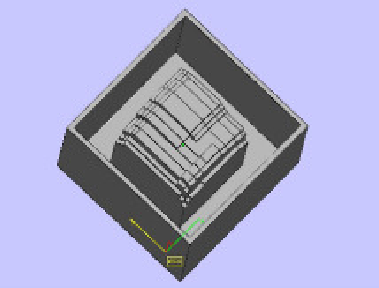

Figure 2. Image of the mold design from a fluency map.

The physical propriety used to define the mold thickness was the exponential attenuation in photons beams provided by any material. Hence,

$$t_{mold}(I) = -\frac{\text{HVL}}{0.693} \times \ln\left(\frac{I}{I_0}\right), \tag{1}$$

where t_{mold} is the mold thickness, *HVL* is the Half Value Layer of cerrobend alloy for 6 MeV photons beams (25 mm), I_0 is the maximum pixel intensity, and I is the pixel intensity in the considered location.

In order to generate a lighter and cheaper block, two other points were considered in the mold algorithm: (1) the maximum intensity region should have no cerrobend attenuation; (2) the maximum height for IMRT cerrobend blocks should be 100 mm. Although some regions can need a higher attenuation, with this cerrobend height it is possible achieve 99% of attenuation for 6 MeV photons beams. Both aspects were considered to generate a lighter block, without compromising the dosimetric quality.

C. *Printing a 3D mold and generating an IMRT compensator block*

The mold information was exported into a stereolithography (STL) file used by Z Corp 3D printer, model 310, which generated a rigid structure of zp®131 powder (Fig. 3).

The mold was filled with a liquid cerrobend alloy (temperature around 90° C), to produce the final IMRT compensator block (Fig. 4). This procedure was done manually to permit a homogenous temperature distribution during this process. While the cerrobend was filling the mold, the table was shaked to avoid formation of air bubbles inside the block volume.

Figure 3. The mold printed in a 3D printer.

(a) (b)

Figure 4. (a) Filling the mold with a liquid cerrobend alloy. (b) The final IMRT compensator block

The block was solid and ready for use after 2 hours. To conclude the manufacture procedure, the mold was broken using basics tools (hammer, spatula).

D. *Quality Assurance*

A dosimetric IMRT QA of the block was performed using GafCromic^{TM} EBT 2 radiochromic film to validate the proposed method. This film was used to measure absolute dose distributions by IMRT compensator block, after a previously dose calibration. The QA was performed by comparing the dose distribution predicted by TPS to that measured using films.

The fluency map provided by the radiation field segments was used in a 30x30x30 cm^3 phantom (created in the TPS with HU = 0). The dose distribution was then computed (source surface distance equal 100 cm), and a dose map at 5 cm depth was exported to the Dicom format. For the measurements, the setup used in the calculation was reproduced in a solid water phantom (30x30x30 cm^3) with a radiochromic film at 5 cm depth (Fig. 5). The radiation exposure time was defined to delivery approximately 250 cGy at the central area, based on the previously calibration film. This present study did not aim at assessing the absolute delivered dose. We are now conducting additional investigations to compare the absolute predicted and attained doses.

In order to assess the agreement between planned and measured dose distributions, 4 horizontal and 4 vertical dose profiles were extracted from the exposed areas. These profiles were normalized in both situations. They were selected in a way that well represents all the area.

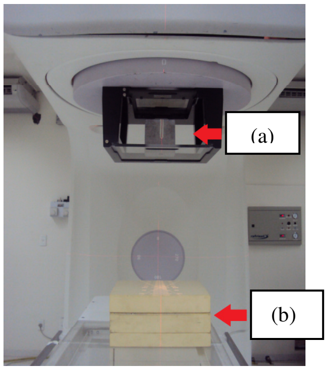

Figure 5. Experimental setup to measure dose distribution. (a) IMRT compensator block, (b) phantom where the dosimetric film was placed.

A displacement in the measured dose distribution was necessary (5 mm to the left, 5 mm up). This was done to compensate an imperfect positioning of the block in the fixation tray. A more general solution was elaborated and already implemented in the mold algorithm for future studies. Finally, the relative dose assessment was done using the RMS error for each pair of profiles.

III. RESULTS AND DISCUSSION

The dose distributions predicted by the TPS and measured with dosimetric film had similar aspect (Fig. 6).

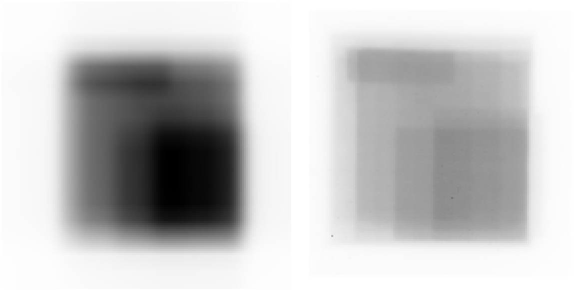

Figure 6. Left: Predicted dose by TPS. Right: Measured dose with film.

The normalized dose profiles computed by TPS and measured with dosimetric films were extracted from Fig. 6. The obtained profiles curves (Fig. 7), with the respective RMS error (Tab. 1), were separated in two columns: horizontal profiles and vertical profiles, respectively.

In a first analysis, we observe that there is a good accordance in terms of the regions with peaks, valleys, and shoulders. Also, the RMS errors obtained were not higher than 8.9 %. Although this value is not too high, a patient IMRT QA only could be accepted with an error up to 3%. The reasons that produced these errors should be associated with: (1) no ideal block thickness, and (2) no divergence in block shape. The block thickness depends on physical properties of the used material. Even the cerrobend's HVL to be well described in literature [3], it is necessary perform some empirical adjustments in the coefficients in Eq. 1.

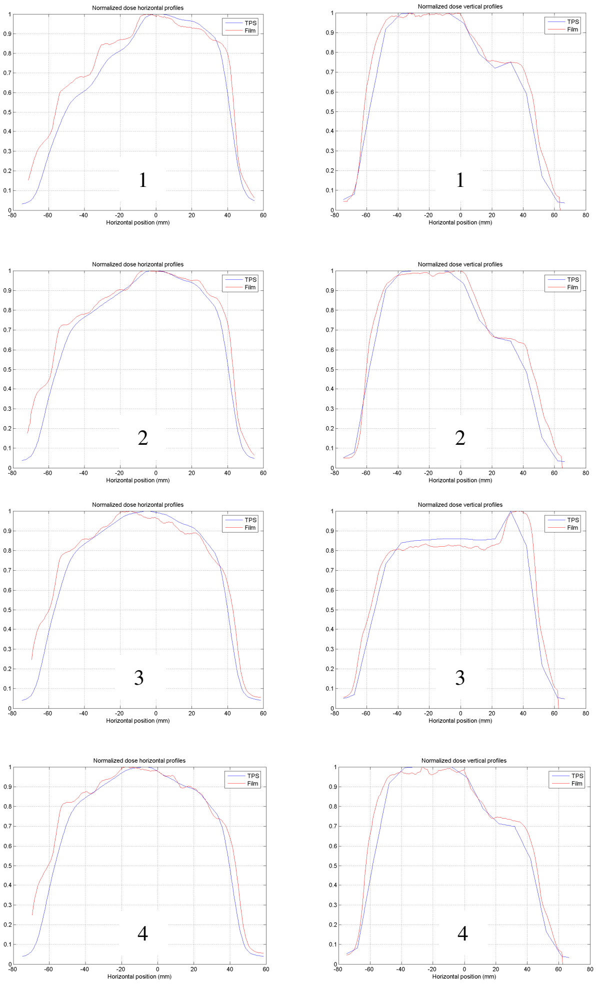

Figure 7. Left: Horizontal Profiles. Right: Vertical Profiles. The red line curves represent the measured profiles. The blue line curves represent the TPS computed profiles.

TABLE I. RMS ERRORS

Profile number	Profile type	RMS error
1	horizontal	0.0884
1	vertical	0.0691
2	horizontal	0.0877
2	vertical	0.0647
2	horizontal	0.0820
3	vertical	0.0795
4	horizontal	0.0870
4	vertical	0.0739

On the other hand, the absence of divergence in block shape enlarged the penumbra region. These aspects are being investigated and implemented in order to adjust the algorithm that converts fluency maps into mold thickness.

Regarding the production costs, we have observed that the final cost of one block manufactured using a 3D printer was approximately 60 percent of the cost for the traditional procedure. Furthermore, the set of blocks for each patient would take around 30 hours to be produced (including the 3D printing, and the block solidification times), while the traditional method takes usually 48 hours. These comparisons do not take into account the transportation costs, as well as the times to deliver the IMRT compensator blocks manufactured outside the hospital. Note that the milling machine is almost never available inside the radiotherapy facilities, while a small 3D printer could be easily available. This represents an important advantage in terms of additional savings, practicality and reduced production times.

IV. CONCLUSION

In this work we developed a systematic method to manufacture IMRT compensator blocks using a 3D printer. This method allows the milling machines, traditionally used for producing compensator blocks, to be replaced by 3D printers, with important advantages. Considering the dimensions of the 3D printer, the IMRT compensator blocks can be fully conducted inside a radiotherapy facility, which results in lower costs and production times. The results showed that adjustments in the block positioning, thickness, and divergence are necessary for clinical use (these adjustments to the algorithm that converts fluency maps into mold are already under implementation). However, the results already show a general agreement between predicted and attained normalized doses, with root mean square errors lower than 8,9 % for the tested profiles.

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