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Original research article

Wax boluses and accuracy of EBT and RTQA radiochromic film detectors in radiotherapy with the JINR Phasotron proton beam

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ABSTRACT

Aim: To present the results obtained using radiochromic films EBT and RTQA 1010P for the reconstruction the dose distributions for targets irradiated by proton beam and modified by wax boluses.
Background: In Medico-Technical Complex at the Joint Institute for Nuclear Research in Dubna implemented technology of wax boluses.
Materials and methods: Wax boluses are easier to make and they give better dose distributions than boluses made from modeling clay previously used at our center. We irradiated two imaginary targets, one shaped as a cylinder and the other one as two cuboids. The evaluated calibration curve was used for calculation of the dose distributions measured by the EBT and RTQA radiochromic film. In both cases, the measured dose distributions were compared to the dose distributions calculated by the treatment planning system (TPS). We also compared dose distributions using three different conformity indices at a 95% isodose.
Results: Better target coverage and better compliance of measurements (semiconductor detectors and radiochromic films) with calculated doses was obtained for cylindrical target than for cuboidal target. The 95% isodose covered well the tumor for both target shapes, while for cuboidal target larger volume around the target received therapeutic dose, due to the complicated target shape. The use wax boluses provided to be effective tool in modifying proton beam to achieve appropriate shape of isodose distribution.
Conclusion: EBT film yielded the best visual matching. Both EBT and RTQA films confirmed good conformity between calculated and measured doses, thus confirming that wax boluses used to modify the proton beam resulted in good dose distributions.

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1. Background

Proton beam radiotherapy (PBRT) has gathered much attention in recent years due to its theoretical advantages over conventional external beam radiotherapy (EBRT). In contrast to EBRT, in which much of the energy is absorbed by healthy tissue as the beam passes through on its way to the target, in PBRT most of the energy is delivered to the target. This pattern of energy deposition, known as the Bragg peak, makes proton therapy especially advantageous in the treatment of tumors surrounded by critical structures.[1,2] For this reason, PBRT is being used in pediatric patients to prevent radiation-induced secondary tumors[3,4] and increasingly in some head and neck tumors as well as for prostate cancer. The major drawback of PBRT is significantly higher price of technology required and also more complicated dosimetry and quality procedures.[2,5,6] In the meantime photon and electron radiotherapy has developed enormously and can offer sophisticated tools which allow on very accurate dose delivery to the target with substantial reduction of dose to critical organs.[7–13]

An important issue in PBRT is in achieving dose conformity in the distal part of the tumor. This difficulty can be overcome by the use of a bolus, which is used to account for heterogenous tissue in the path of the beam and to adapt the proton range to the shape of the tumor. The ideal bolus should be made of safe, tissue-equivalent material that is durable, cost-effective, and sufficiently flexible to conform to the patient's body. Up until quite recently, at our center boluses were made of modeling clay. However, the high plasticity and low melting point were sometimes problematic. In addition, the bolus was formed partially by hand and thus lacked precision. To overcome these shortcomings, we recently switched to a different material – special wax for machine processing. Wax boluses have numerous theoretical advantages: they are milled by a computerized machine that produces a precisely-made bolus in accordance with the treatment plan coordinates (x, y, z). In addition, wax boluses have a higher melting point than modeling clay boluses (116 °C vs. 65 °C), and they are more resistant to mechanical injury.

Accurate dose determination and precise dose delivery are essential in all types of radiotherapy,[7] but particularly in PBRT due to the patterns of energy deposition. For this reason, numerous dose verification and calibration methods have been created. ICRU 59 describes the use of ionization chambers for proton dosimetry,[8] although other methods, such as semiconducting detectors, can be used for this purpose. However, in recent years, improvements in radiochromic film (RCF) dosimetry have made this technique a powerful tool for treatment verification and quality assurance. RCFs are used in conventional radiotherapy with photons, but they are also good detectors for the dosimetry of the proton beam because they can be positioned along the beam axis in a water phantom.[9,14] Several authors have described different types of radiochromic films to measure proton dosimetry, including Vatnitsky et al.[15] and Ciangaru et al.[16] The advantages of RFCs are that they are sensitive to ionizing radiation, and change color in response to the delivered radiation, with darker colors indicative of higher doses. Moreover, RCFs are easy to handle and prepare because they are not sensitive to room lights, they develop automatically (unlike radiographic films), and facilitate reading of the absorbed dose. Several different types of RCF have been developed, with two of the most common being EBT and RTQA radiochromic films.[17]

2. Aim

The present study had two primary aims: (1) to evaluate the ability of wax boluses to produce a specific dose distribution; and (2) to compare two types of radiochromic films used to verify the accuracy of the calculation algorithm for the proton beam at our center (Medico-Technical Complex of the Joint Institute for Nuclear Research at Dubna, Russia).

3. Materials and methods

3.1. *Treatment planning system, targets, conditions of irradiation*

We used the TPN 3D treatment planning system (TPS), developed at the Loma-Linda University Medical Center, California, USA. This TPS was adapted for proton beams delivered by the JINR Phasotron with output energy of 660 MeV. For medical applications the energy of protons is reduced to 175 MeV and such beam was used in the study.

For this study, we created two distinct shapes for the irradiated targets and a separate treatment plan for each of them. Both shapes were basic geometric figures with a volume of about 125 cm^3, and they are shown in Fig. 1.

Measurements were made in an almost tissue-equivalent environment (water). The geometric targets were virtually immersed in a PMMA tank with internal volume of 254 mm × 160 mm × 201 mm produced at the MTC workshop. The tank was filled with water for the irradiation process. We used a 60 mm × 60 mm collimator with a ridge filter to spread-out the proton beam Bragg peak to the size of targets.

3.2. *Wax boluses*

Boluses are produced individually for each patient and for each irradiation angle. Boluses were mechanically milled to match the coordinates calculated by the TPS. The boluses used in the study are presented in Fig. 2.

3.3. *Dosimeters*

We used two types of RC films: EBT and RTQA 1010P (International Specialty Products, Wayne, NJ, USA) to measure dose distributions. These films can be used in a water environment because the film layers are not affected by water. EBT film consists of two active layers (i.e., responsive to radiation) and two outer layers of transparent polyester. RTQA film has one active layer and one layer of transparent polyester, colored in yellow and one layer of white nontransparent polyester.

3.4. *Calibration of detectors*

Films were cut into 8 small pieces 20 mm × 20 mm in dimension and were irradiated with the following doses: EBT films

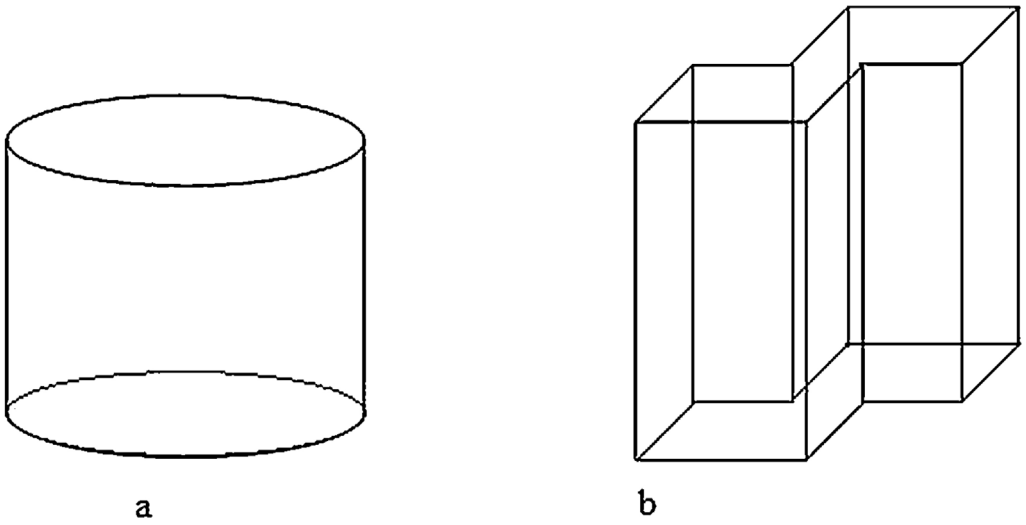

Fig. 1 – Shapes of irradiated targets: (a) a cylinder with the diameter of 50 mm; (b) two cuboids with base square 25 mm x 25 mm offset from each other by 15 mm.

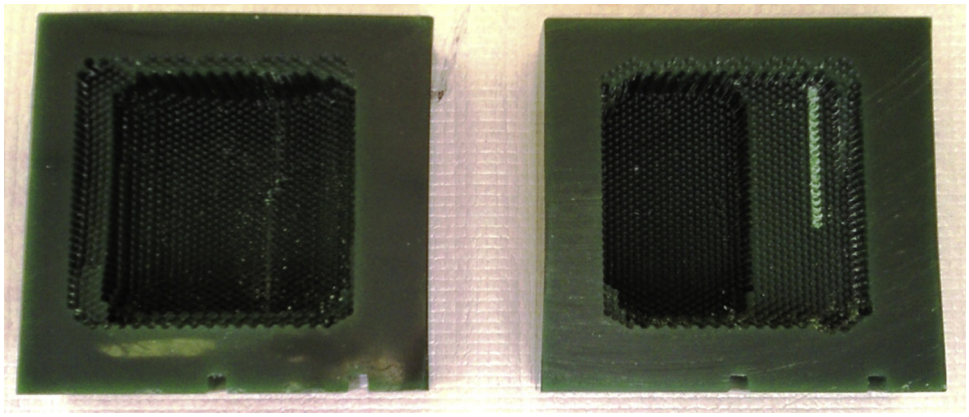

Fig. 2 – The boluses used in the study.

(0-3.0 Gy) and RTQA (0-3.5 Gy). These small pieces were used to define how the film responds to the indicated dose and to calibrate the detectors and scanner at the same time. One piece of each type of radiochromic film was left unirradiated in order to characterize a 0 Gy dose. The other pieces were irradiated perpendicularly to the central axis of the beam. Forty-eight hours after irradiation, the pieces were scanned and the red channel (which offers the highest absorption) was extracted from the Red–Green–Blue bitmap using dedicated software for image processing and analysis in Java (ImageJ) and pixel values were read in order to calculate the relative optical density (ROD) and to draw the calibration curve (representing the relation between ROD and dose, as shown in Fig. 3). The films were scanned on the flatbed scanner (HP Officejet 7213).

3.5. *Dose distribution measurements*

Next, larger pieces (100 mm × 170 mm in dimension) were cut from an RCF sheet and were irradiated with a 3 Gy dose (at the isocenter) in order to verify dose distributions. Films were places in the water phantom and positioned with a 5° slope

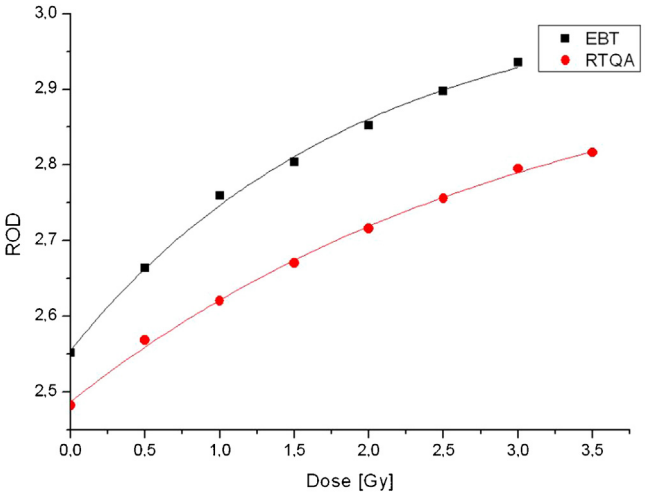

Fig. 3 – Calibration curves for EBT and RTQA radiochromic films.

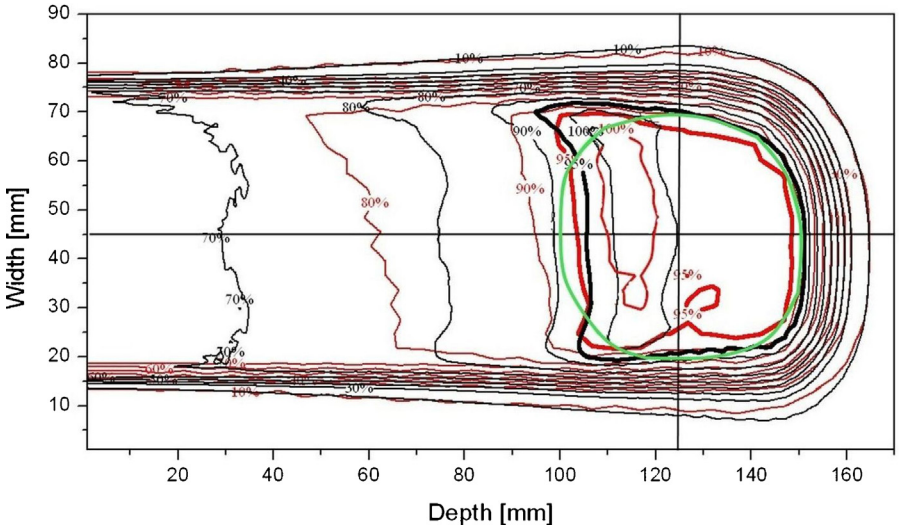

Fig. 4 – Dose distributions of TPS and semiconductor detector for 1st case (cylindrical target).

to the beam axis in the horizontal plane, which prevented a formation of air gaps under the films. After 48 h, all films were scanned with the same orientation on a 48-bit flat bed scanner at a resolution of 200 dpi. To perform verification of the dose distributions, we created bitmaps from the scanned images, reduced the resolution to correspond the resolution of the calculated dose fields, and cut the red channel.

For comparative purposes, we also used high-doped p-type silicon semiconductor detector (<1 mm thick) to measure dose distributions. The detector was placed in the water phantom and was continuously repositioned during irradiation (via a small motor) perpendicularly to the beam axis in steps of 3 mm and parallel to the axis with steps of 5 mm. Position of detector was changed to measure a level of dose in different points and next to create 2D dose distribution map parallel to the beam axis.

3.6. *Dose distribution comparison*

To verify the fit of the dose distribution to the target for beams modified by wax boluses, we analyzed the coverage of the tumor by the isodose of 95%. Use of the 95% isodose as reference value corresponded well with the methodology of fitting "dose to structures" with the use of conformity indices i.e. Radiation Therapy Oncology Group conformity index (CI_{RTOG}), the healthy tissue conformity index (HTCI), and the two-component conformity index (TCCI), etc.[18] We decided, however not to apply the particular indices because the study was carried out for the artificially shaped tumor only structures, that could not be checked well by conformity indices.

4. Results

4.1. *Film calibration*

Fig. 3 shows the calibration curves for both films. This curve shows the relation between optical density and dose. As can be seen in the figure, response to radiation is higher on the EBT film than the RTQA film. For example, at an irradiation dose of dose of 1.5 Gy, the ROD for EBT and RTQA, respectively, were 0.395 and 0.262. The fitted curves represented solid lines which are asymptotes ($y = a - b \times c^x$). The ROD values were calculated from the values of pixels in the red channel of the 48-bit scan.

4.2. *Graphical comparison of dose distributions between TPS and detectors*

Figs. 4 and 5 compare the expected dose distribution (TPS) and the doses measured by the semiconductor detectors for the cylindrical (Fig. 4) and cuboidal (Fig. 5) targets. Black lines represent the calculated dose from the TPS and the red lines the measured dose recorded by the detectors. The green line is the tumor area. Bolded lines show the 95% isodose (2.85 Gy) of the dose at the isocenter (3.00 Gy). Tumor volume is covered by high dose of 95% for both analyzed shapes. TPS calculated dose distribution for cuboidal target reference isodoses covered also considerable area around the target.

Figs. 6–9 compare the dose distributions calculated by the TPS and the distributions actually measured by the Gafchromic films for the cylindrical (Figs. 6 and 7) and cuboidal (Figs. 8 and 9) targets. The black lines represent the calculated dose by the TPS and the red lines – the measured dose recorded by the RC films. The green line is the tumor area. Only selected isodoses are presented. The bold lines show the 95% isodose of the maximum dose, which was normalized at 3.00 Gy in the isocenter.

We observed that for lower doses (10–50% of the prescribed dose) for both targets were located at the same places, regardless of whether measurement was performed with a silicon detector or RCF. For the first target (the cylinder), 95% isodoses included the target plus a small area outside but near the target whereas in the second case (the cuboids), 95% isodoses (i.e., 2.85 Gy) included part of the target but also a larger area near the target. Fig. 9 shows this well: the maximum dose of 3 Gy measured by RTQA film lies outside the contoured tumor.

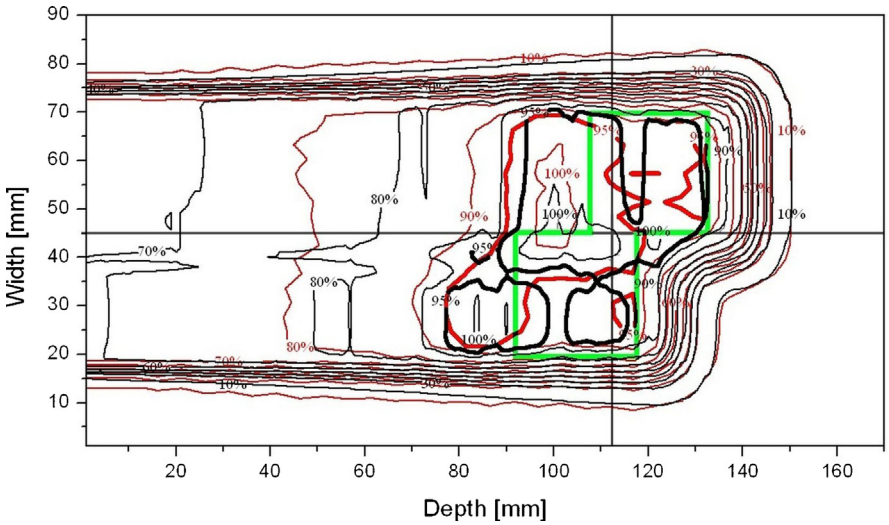

Fig. 5 – Dose distributions of TPS and semiconductor detectors for 2nd case (cuboids).

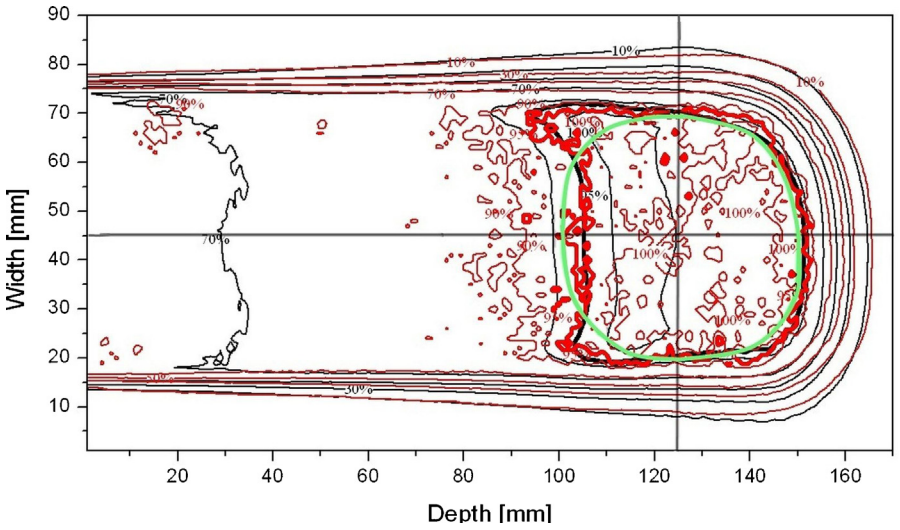

Fig. 6 – Dose distributions of TPS and EBT film for 1st case (cylindrical target).

5. Discussion

We were able to measure the dose distribution in the entire plane along the beam axis using both silicon detectors and RCFs. However, dose distributions were more precise with the RCFs because these sheets are able to capture the dose over the entire area of the film whereas silicon detectors can only measure the dose at a specific location, resulting in less precise spatial resolution.

5.1. *Radiochromic films*

The benefits radiochromic films are numerous. Originally created as a replacement for silver halide radiographic film for use in quality assurance (QA) in intensity modulated radiotherapy (IMRT), EBT films are now widely used in various types of dosimetric QA.[19] Unlike radiographic films, they are auto-developing, with the film changing color in dose-dependent manner.[20,21] Their thin and flexible profile permits for sandwiching the films between solid phantoms of diverse geometric shapes, and they are also unaffected by water and so are suitable for immersion in water phantoms. Radiochromic films are nearly tissue equivalent and spatial resolution is high, thus making them ideal for measuring dose distributions with steep dose gradients as occurs with the Bragg peak in PBRT; according to Vatninski et al., RCF dosimetry can detect misalignments >2 mm.[15] Moreover, RCFs are unaffected by standard room lights, although they are sensitive to UV radiation in sunlight and glow-tube lighting.[14,15,22]

5.2. *Comparison of measured and calculated doses*

The coverage of the target by reference isodose (95% of the dose in the isocenter) was better for the cylindrical target shape than for the cuboidal one. Of the three applied dosimetric methods: EBT, RTQA, and semiconductors, the EBT films

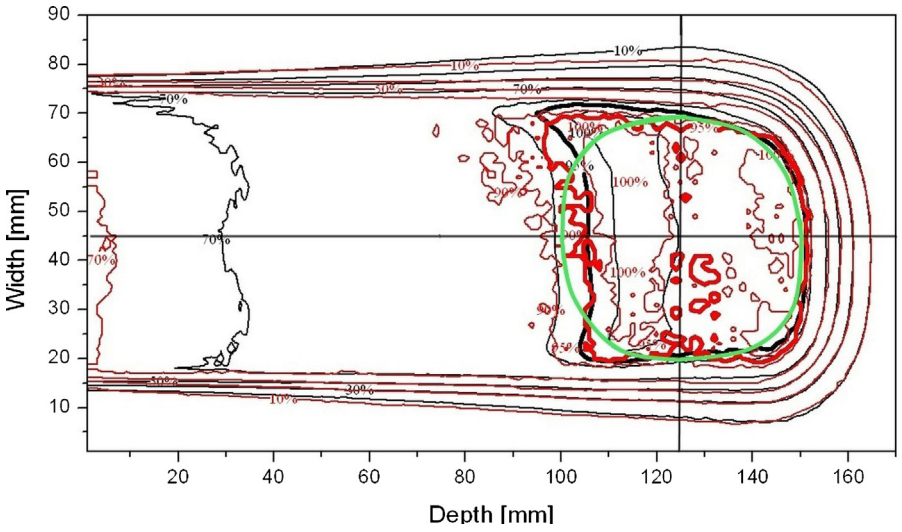

Fig. 7 – Dose distributions of TPS and RTQA film for 1st case (cylindrical target).

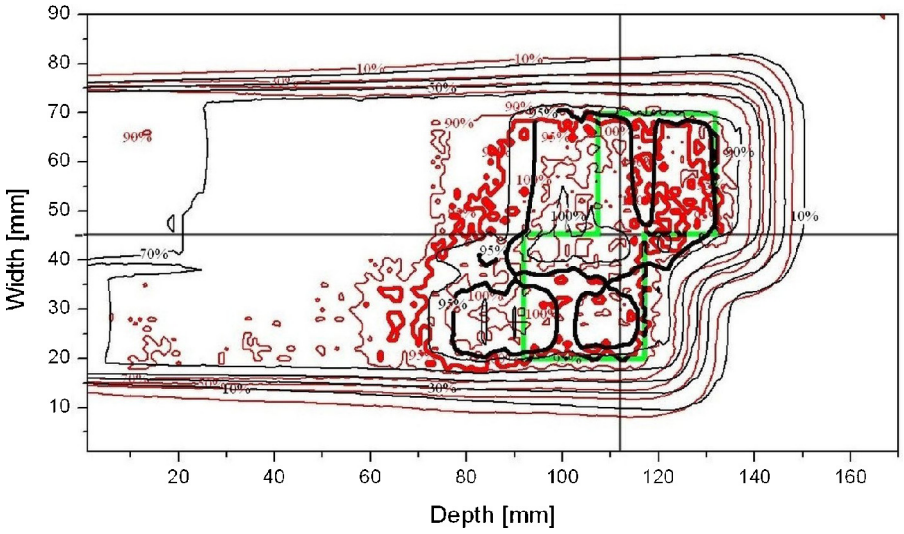

Fig. 8 – Dose distributions of TPS and EBT film for 2nd case (cuboidal target).

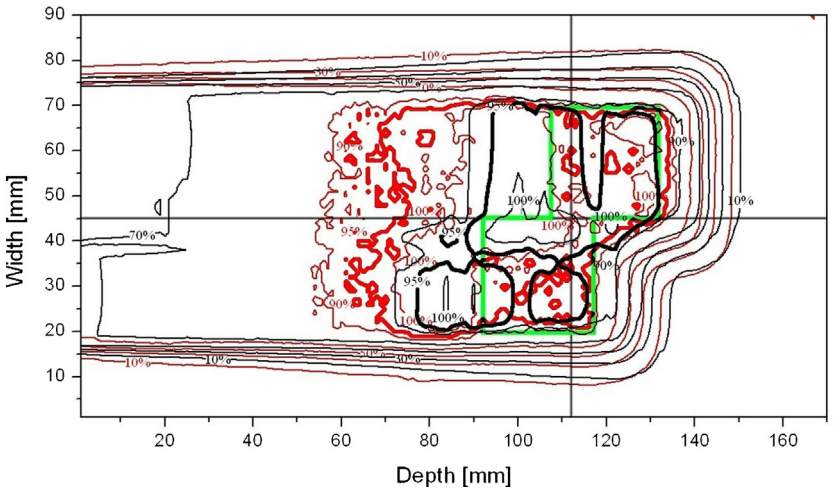

Fig. 9 – Dose distribution of TPS and RTQA film for 2nd case (cuboidal target).

provided the dose distribution with best compliance, particularly for the cylindrical target. In contrast, the coverage of the cylindrical target as revealed by the silicon detectors differed from a dose distribution calculated using the TPS by a noticeable deviation.

In the cuboidal target, all types of detectors gave a good coverage by a referential isodose, few findings to be highlighted. The distributions measured by silicon detectors showed the largest deviation from the TPS doses while RCF films doses fitted the most.

5.3. *Usefulness of wax boluses*

Good compliance between the target shape and isodose coverage, as revealed by the good coverage of the targets by 95% isodose (shown in Figs. 4–9), supports the usefulness of wax boluses. Nevertheless, the repeated measurements for the structures created not only for the tumors but also representing critical organs would extend knowledge on usefulness and accuracy of applied methodology.

The wax boluses used to modify proton beams at our center have been proven to be suitable for modifying proton beam range. They were able to accurately reproduce the distal age of the tumor and dose distribution was good for targets with streamlined shapes, which is crucial for treatment of brain tumors where the dose must be precisely delivered.

6. Conclusions

This study has shown that EBT radiochromic films are accurate and reliable manner to verify the dose distribution of proton beams. We confirmed that the wax boluses creating and using at our center provide dose distributions that are very close to those calculated by the TPS. These results also show that the TPS algorithm used at our center is correct.

Conflict of interest

None declared.

Financial disclosure

None declared.

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