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Monte Carlo flattening filter design to high energy intraoperative electron beam homogenization

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A R T I C L E I N F O

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A B S T R A C T

Intraoperative radiotherapy using mobile linear accelerators is used for a wide variety of malignancies. However, when large fields are used in combination with high energies, a deterioration of the flatness dose profile is measured with respect to smaller fields and lower energies. Indeed, for the LIAC HWL of Sordina, this deterioration is observed for the 12 MeV beam combined with 10 cm (or larger) diameter applicator. Aimed to solve this problem, a flattening filter has been designed and validated evaluating the feasibility of its usage at the upper part of the applicator. The design of the filter was based on Monte Carlo simulations because of its accuracy in modeling components of clinical devices, among other purposes. The LIAC 10 cm diameter applicator was modeled and simulated independently by two different research groups using two different MC codes, reproducing the heterogeneity of the 12 MeV energy beam. Then, an iterative process of filter design was carried out. Finally, the MC designed conical filter with the optimal size and height to obtain the desired flattened beam was built in-house using a 3D printer. During the experimental validation of the applicator-filter, percentage depth dose, beam profiles, absolute and peripheral dose measurements were performed to demonstrate the effectiveness of the filter addition in the applicator. These measurements conclude that the beam has been flattened, from 5.9% with the standard configuration to 1.6% for the configuration with the filter, without significant increase of the peripheral dose. Consequently, the new filter-applicator LIAC configuration can be used also in a conventional surgery room. A reduction of 16% of the output dose and a reduction of 1.1 mm in the D_{50} of the percentage depth dose was measured with respect to the original configuration. This work is a proof-of-concept that demonstrates that it is possible to add a filter able to flatten the beam delivered by the Sordina LIAC HWL. Future studies will focus on more refined technical solutions fully compatible with the integrity of the applicator, including its sterilization, to be safely introduced in the clinical practice.

1. Introduction

Intraoperative electron radiotherapy (IOeRT) is a technique that consists in delivering a single high radiation dose to the residual tumor or tumor bed during surgery. The direct visualization of the area exposed allows the precise localization and targeted delivery of high dose radiation to the tumor bed while minimizing the exposure of surrounding normal tissue that are displaced away from the tumor bed or

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shielded during the irradiation. Therefore, the dose escalation without increasing normal tissue complications results in an improvement of the therapeutic ratio (Pilar et al., 2017), (Calvo, 2017), (Sanchis et al., 2019a).

The use of mobile linear accelerators has led IOeRT to become a widespread technique. This is due to the fact that these accelerators can be employed in a conventional surgery room without any additional shielding considerations. This eliminates the need of moving the patient to a different shielded operating room maintaining the proper sterilization that is required during its transport (Sanchis et al., 2019b).

IOeRT can be applied exclusively or as a boost in combination with fractionated external radiotherapy. This technique is indicated clinically for a wide variety of malignancies such as breast, lung, pancreas, gastric, central nervous system, head and neck, bile duct, bladder, colorectal, gynecologic, genitourinary, pediatrics, extremity and trunk soft-tissue, retroperitoneal and bone (Gunderson et al., 2011), (Calvo, 2017).

One of the clinical indications for the use of IOeRT is the treatment of sarcomas. In these cases, the irradiation area is significantly large, so the largest applicator sizes have to be used. In fact, for some accelerator models there are special square and rectangular applicators for this type of treatment. In some cases, due to the huge dimensions of the treatment area it may be even necessary to join two radiation fields, leading to a geometric uncertainty and the underdosification or overdosification in the junction of both fields.

The most common scenario in IOeRT is the prophylactic one, that is, the irradiation of the tumoral bed following removal of the tumor during surgery. However, in some cases, residual tumor may remain due to the proximity of critical organs or the difficulty of the intervention itself. Therefore, the treatment depth is greater and the highest energies available must be used. In the specific case of some accelerators, such as the one used in this study, the combination of large fields and high energies produces a deterioration of the flatness dose profile obtained with respect to lower energies and smaller fields.

The motivation for this work stems from the possibility of solving the loss in beam flatness obtained for large fields and high energies by using a flattening filter at the upper part of the applicator.

2. Material and methods

2.1. Mobile linac

LIAC HWL (SIT, Sordina IORT Technologies, Vicenza, Italy) is a mobile accelerator for intraoperative radiotherapy treatments (Winkler et al., 2020), (Mastella et al., 2022). This model has been designed to minimize stray radiation (<0.2 μSv/Gy in patient plane at a distance of 3 m) (LIAC HWL Mobile Ioert Accelerator, 2022), allowing a workload higher than 100 Gy/week according to NCRP 151 standard (NCRP Report Nº151, 2005). Therefore, the only structural barrier required is the beam stopper in order to protect downward areas. The previous characteristics, together with its light weight and small dimensions, allow it to be used in a conventional operating room. The LIAC HWL available at the Hospital Universitari i Politècnic La Fe of València is the 12 MeV model, which allows the use of four energies: 6 MeV, 8 MeV, 10 MeV and 12 MeV.

Collimation of the radiation beam is achieved by cylindrical-shaped PMMA applicators, which consist of two parts (upper and lower) connected by a hard docking junction. The overall applicator length is 40 cm and the diameter size ranges from 30 mm to 100 mm. There are four different bevel angles available (0°, 15°, 30°, 45°).

2.2. Monte Carlo simulations

Monte Carlo (MC) simulations have become the gold standard for many applications in the field of medical physics, such as radiation protection, treatment planning systems or the design of clinical systems, among others. In particular, they offer one of the best and more cost-efficient methods to determine the geometrical requirements of a filtering structure (Spezi et al., 2001), (Verhaegen and Seuntjens, 2003). Therefore, these techniques have been widely applied when designing flattening filters in photon-based radiotherapy (McCall et al., 1978), (Granero et al., 2008) and to a lesser extent in electron-based ones (Hsu et al., 1995). In this work, state-of-the-art MC simulations have been used to design a specific filter tailored to flatten the beam produced by the aforementioned LIAC. As a proof of concept, the specific scenario for large fields and greater prescription depths, that force the use of higher beam energies in clinical practice have been considered, namely 10 cm in diameter and 12 MeV.

To rule out any possible inconsistency and also to determine the relevance of any possible source of Type B uncertainties related with the MC simulations, two different MC codes were used independently by two different research groups. Notice that Type B uncertainties referred to those that are estimated using some means other than statistical treatment of the results, while Type A uncertainties refers to any method for evaluating uncertainty using statistical analysis of a series of observations. The codes used for this purpose were, penEasy (v20200325) (Sempau et al., 2011), a modular code for the PENELOPE2018 system (Salvat, 2019) and MCNP6 (version 2) (Los Alamos Scientific Laboratory Group X-6 Los Alamos, 1979). Those MC codes have been extensively described and benchmarked in the literature (Sempau et al., 2003), (Solberg et al., 2001).

For both codes, the particle source of the simulation was the electron 12 MeV phase space file (PSF) provided by the manufacturer at the exit of the LinAc head (Iaccarino et al., 2011) located just before the mobile LinAc applicator. The dimensions of 10 cm in diameter applicator (A10) were measured using a caliper (having a precision of 0.005 cm) and modeled into the simulation together with a $20 \times 20 \times 20$ cm^3 water phantom placed in contact with A10. The depth dose and the dose profile curves along the water tank were tallied using a voxel size of 1 mm^3 for both MC codes. Dose profile was obtained at the maximum of the depth dose, which is achieved at 17 mm from the water tank surface. The applicator and the filter are modeled as PMMA (density of 1.19 g cm^{-3}), while the phantom as standard water (ICRU 90, 2016). All the simulations were performed considering a cut-off energy of 200 keV for electrons and 10 keV for secondary photons in all materials. These being scattered photons produced mostly by bremsstrahlung. Characteristic X-rays and photons due to electron-positron annihilation are also present, but in a smaller numbers. Type A uncertainties of about 0.1% ($k = 2$) were achieved, where $k = 2$ produces an interval with a level of confidence of approximately 95%. Differences between MC codes reported for different 12 MeV electron beams are in the range of 2% or lower for the depth dose and the dose profile (Sempau et al., 2001) outside of the penumbra region. These results allow estimating a conservative combined uncertainty of 2% ($k = 2$) for the MC simulations.

2.3. Monte Carlo validation and filter design for LIAC 12 MeV electron beam and A10

As it will be shown in the next section 3.2, Fig. 4, the inhomogeneous profile at the maximum of the depth dose shows higher dose absorption at the center of the radiation field than in its periphery. Therefore, a conical filter was considered to be the best candidate to be added to the original applicator geometry.

The first step was to ensure the correctness of the applicator geometry and the corresponding material assignment in both MC codes. To do so, the depth dose and dose profile curves calculated in the water tank were compared with experimental data measured at the Hospital Universitari i Politècnic La Fe. The experimental measurements were carried out in an MP3 water tank (PTW-Freiburg, Germany) using a reference chamber of PTW (31010 Semiflex) and E Diode type 60012. The beam used for MC validation was 12 MeV PSF at the exit of the linac head containing both electron a photon particles which is collimated with the A10.

Once the dose curves of both MC codes were validated, an iterative process of filter design was carried out. First, a set of simulations adding cylinders of variable thickness were performed to evaluate their dosimetric effect. Once this information was available, a combination of cylinders with different radii and thickness was explored to achieve global flatness. The last step implied combining those into a cone for ease of construction.

Finally, the MC designed filter with the optimal size and height to obtain a flattened beam at 17 mm from the water tank surface was manufactured in-house using a 3D printer Prusa MK3s+ (Prusa Research, Prague, Czech Republic) using Fervi 3D Pla Esencial (polylactic acid) (Alicante, Spain) with a density of about 1.3 g cm^{-3}. The nozzle used was the standard one provided, having a size of 0.4 mm. Using this nozzle, layer heights between 0.05 and 0.35 mm were achievable, although heights below 0.1 mm proved difficult to be obtained without imperfections. Dimensions were checked using a Mitutoyo QV Accel 808 (Mitutoyo Europe GmbH, Neuss, Germany) measuring system up to a tolerance of 50 μm. Minor modifications were required afterwards to improve its robustness and stability once installed in the applicator.

2.4. Filter experimental validation and impact on clinical beam

To demonstrate the effectiveness of the designed filter this section describes the experimental measurements carried out with the standard and flattening filter A10 with no bevel.

Percentage depth dose (PDD), beam profiles, absolute and peripheral dose measurements for a 12 MeV electron beam were performed for the standard and flattening filter applicator to evaluate the possible impact of the filter on the depth dose.

2.4.1. Experimental setup

PDDs and absolute dose measurements were carried out in an MP1 water tank (PTW-Freiburg, Germany). The commissioning measurements were carried out with the recommended detectors, namely the ionisation chambers and the electron diode. Absolute dose measurements for 500 monitor units (MU) beam irradiation were conducted with either Advanced Markus chamber type 34045 and E Diode type 60017 at 17 mm depth. Both detectors were coupled to a T10008 Unidos electrometer (PTW, Freiburg).

Attenuation factor was determined as the relative difference of the average absolute dose measurements for the standard and flattening filter design applicator. PDDs were measured from water surface to a depth of 8 cm along the central axis using Advanced Markus chamber. Data measurements were analyzed by Mephysto software (PTW, Freiburg). Measured shift in PDD curves ($z_{standard}(D_{50}) - z_{filter}(D_{50})$) was calculated. The experimental setup is the same as described before.

For the verification of the impact of the filter, pieces of GAFChromic EBT3 film (Ashland Inc., Bridgewater, NJ, USA) were used, which allows to obtain the dose profiles at zero depth of the water tank to evaluate the variation in the low energy electron components.

2.4.2. Measurements for experimental validation

To obtain radiation dose profiles, two pieces of GAFChromic EBT3 were exposed to 330 MU to deliver approximately 3 Gy, at a depth of 17 mm in a RW3 solid water phantom. One film was irradiated using the applicator with the flattening filter, while the other was irradiated with the standard applicator. The films were handled, scanned and calibrated in accordance with the protocol detailed by Méndez et al. (2021). Calibration was conducted using seven slices of film irradiated with the LIAC HWL to deliver absorbed doses ranging from 0 to 3.5 Gy. Film doses were obtained using the radiochromic film dosimetry web application, Radiochromic.com (Radiochromic SL, Benifaió, Spain), which converts film images into doses using the Multigaussian model (Méndez et al., 2018). An Epson Expression 12000XL flatbed scanner manufactured by Seiko Epson Corporation (Nagano, Japan) was employed for scanning. The estimated combined uncertainty for the experimental data was 4% (k = 2).

Finally, the beam flatness defined as half of the difference between the maximum and minimum dose values across the 80% of the field size, was measured.

2.5. Filter impact on stray dose

As mentioned before, one of the main features of the LIAC HWL mobile linac is that has been designed to minimize stray radiation. Therefore, peripheral dose measurements were performed in order to verify that the addition of the filter into the applicator does not cause any change in the amount of bremsstrahlung radiation generated during beam irradiation. Three irradiations of 300 MU on solid water phantom were performed for each applicator. Maximum dose rate measurements were performed at 3 m distance with a INOVION 451 survey meter (Fluke Biomedical, USA). In front of the detector, 5 cm solid water slabs were placed to shield the leakage low energy electrons. The experimental setup for these measurements was the same that in a previous work (Garcia-Gil et al., 2022). The ratio of the average maximum dose rate measurement between both applicators was obtained. The statistical uncertainty of the ratio was lower than 2%.

3. Results

3.1. Monte Carlo validation and filter design

First, the simulations with no filter have been carried out with a Type A uncertainty lower than 4% (k = 2) in the region of interest for both codes. These ones shown agreement within the uncertainties, differences smaller than 1% at the maximum of the depth dose. In addition, taking into account an estimated Type A and B combined uncertainty of 4% (k = 2) for the experimental measurements, the MC simulations provided compatible results. Therefore, it was established that both MC codes reproduce the experimental data, validating the simulation parameters used and the applicator geometry and material assignation.

Then, to obtain the final design of the filter, the dose profiles at the maximum of the depth dose and its proximities were analyzed. Finally, both codes conclude that a conical filter with 1.3 mm of height located at 3 cm from the top of the upper part of the applicator produces a flat dose profile at 17 mm from the water tank surface. The depth dose and dose profiles values obtained using the simulated final filter show that results of both codes are compatible within the MC uncertainties. These MC-based doses were also compared with the experimental depth dose curve and dose profiles. In both cases MCNP and penEasy/PENELOPE simulations are in good agreement with the experimental results within MC combined uncertainty of 2% (k = 2) and combined uncertainty estimated for experimental data of 4% (k = 2).

The final filter profile together with the experimental verification of the dimensions of the printed versions are shown in Fig. 1.

Fig. 2 shows the final filter design printed in PLA with the 3D printer Prusa MK3s+. The filter has been embedded in the upper part of A10 to perform the experimental validation. The location of the filter is the one used for the MC simulations. Fig. 3 shows both, the applicator with the designed filter and the standard applicator. The filter is located on top of the conical indentation inside the applicator. Being printed with the exact inner dimensions of the applicator it remains in place without using any additional measure independently of the orientation of the device.

3.2. Experimental validation of the filter and impact on the clinical beam

For each applicator configuration, Fig. 4 shows the experimental dose profiles obtained by averaging the dose values of every point of the irradiated film at the same distance from the beam center. The dose average values and their corresponding standard deviations, also plotted

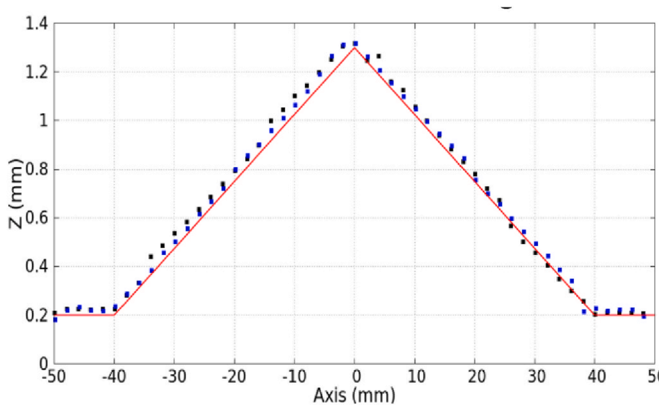

Fig. 1. Lateral profile of the conic filter designed. Red solid line corresponds to the MC geometry implemented in the simulation. Dots correspond to the experimental measurements performed as described in Section 2.4. Black dots correspond to measurements along the Y axis and blue ones along the X axis. The grid dimensions are not the same.

Fig. 2. Printed PLA (density of about 1.3 g cm^{-3}) designed filter which has been added to the A10 LIAC. The filter presents a conical shape with 1.3 mm height at the center.

in Fig. 4, confirm the cylindrical symmetry of the flattening filter. Beam flatness obtained was 5.9% and 1.6% for the standard applicator and the applicator with the flattening filter, respectively.

To better show the dose profile results, only half-profiles are displayed in Fig. 4. Moreover, for the sake of clarity and due to the agreement between MC codes, only penEasy/PENELOPE results are presented. Fig. 4 lower plot, shows the experimental profile measured with the applicator-filter configuration and the MC profile obtained including the filter in the applicator.

The combined Type A and B uncertainty estimated for the experimental data is 4% (k = 2) and for the MC results is 2% (k = 2).

Fig. 3. The two upper part of the A10 of the LIAC used in this work. The top image shows the top view of both A10, with the designed filter embedded and the standard one. The bottom image shows the opposite view.

In terms of the absolute dose comparison for both applicator configurations in the central axis ($r = 0$ cm), MC, film, Advanced Markus and E Diode results show that a reduction of a 16% of the dose is produced due to the filter addition. Moreover, comparison of PDD results show 1.1 mm reduction in D_{50} due to the filter addition.

3.3. Filter impact on stray dose

Measurements performed at a distance of 3 m using the standard applicator gives a value of 0.13 μSv/Gy, well below the nominal value stated by the manufacturer (<0.2 μSv/Gy). It is interesting to note that the value provided by the manufacturer includes an associated uncertainty of about 20% due to different sources included in the set-up, calibration of the detector and small differences in the spectrum generated by the LIAC. Measurements performed using the modified applicator including the flattening filter gives a value 2.6% higher than the standard one, which is well below the manufacturer's nominal value and negligible when the typical experimental uncertainties are taken into account.

Such negligible increase in scattered radiation validates the potential use of the filter without generating a radiation protection issue.

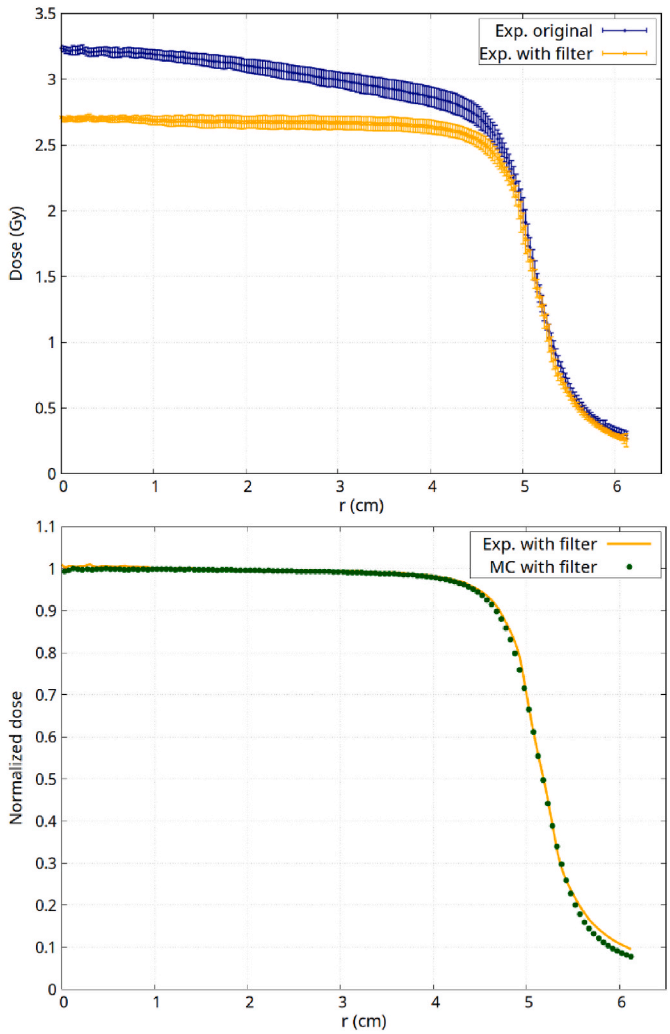

Fig. 4. Experimental measures with the original LIAC configuration and with the addition of the filter, showing a 16% dose reduction in the center of the beam (top). Normalized experimental dose profile with filter and normalized MC dose with filter (bottom). The combined uncertainty estimated for the experimental data is of 4% (k = 2), and for MC results is 2% (k = 2). Error bars are not shown for the sake of clarity (bottom).

4. Discussion

The feasibility of a flattening filter design has been evaluated for a LIAC mobile accelerators to solve the inhomogeneity problems for large fields and high energy beams. The filter addition technique has been widely used in other clinical devices. For example, in the case of the Leipzig applicators (Niu et al., 2004), (Pérez-Calatayud et al., 2005) a filter was added to flatten the dose distribution, resulting in the Valencia applicators (Granero et al., 2008), both produced by Elekta Brachytherapy (Veenendaal, The Netherlands). This technique has been applied also for the Mobetron (Intraop Medical Corporation, Sunnyvale, CA) intraoperative linac sarcoma applicators (Janssen et al., 2008). In that study an additional scattering foil was added on the top of a prototyped rectangular applicator to obtain the desired field flatness comparable with the standard A10.

In this work, following an analogous procedure, a prototype flattening filter has been added to the upper part of the A10 of the Sordina LIAC HWL accelerator available at the Hospital Universitari i Politècnic La Fe of València for the 12 MeV energy beam. The results of the case studied show a flat profile for the experimental measurements when the applicator-filter configuration is used. Notice that the dimensions of the designed filter depend on its materials, the energy beam and applicator size. Any modification of these parameters in the LIAC configuration would require a new process of MC simulation design and experimental validation of the resulting filter.

In addition to the homogeneity achieved in the beam due to the designed filter, the increase of the peripheral dose around the device is considered negligible. Therefore, the applicator-filter LIAC HWL configuration maintains the necessary conditions to be used in conventional operating rooms in the same way as the original ensemble.

Although the strategy of adding a flattening filter is not new in radiotherapy, the novelty of the present work lies in its application to the case of intraoperative radiotherapy using simple and inexpensive acrylic applicators. In the case of portable electron accelerators, such as the one considered in this work, the preservation of peripheral dose is fundamental given their use in unshielded rooms and the filter design is a challenge in the face of additional sources of scatter, such as a filter.

After initial testing, it turned out that a cone-shaped design was sufficient for homogenization purposes, avoiding more complex solutions (i.e. Gaussian shape, concentric rings …) that would affect robustness and complicate manufacturing to a greater degree. For the design and verification of the filter it has been necessary to apply the Monte Carlo method given the complexity of the various components of the electron beam coming from the accelerator head and applicator, and no other more reliable and direct process has been found.

A possible limitation of this work is the complexity to accurately model the material available for constructing the filter. For all the simulations carried out the filter material has been assigned to PMMA while the final printed filter was made of commercial PLA. The PLA is an organic material widely used in 3D printing, made from fermented plant starch from maize, corn or cassava, among others. Since the composition of the particular batch used cannot be known precisely, PMMA was used in the MC simulations due to the similarities between both plastics, as well as their relatively close density values. This simplification has been supported a posteriori by the experimental validation performed.

Since the Sordina LIAC HWL has not include equalizing filter, this work is a proof-of-concept of the feasibility of adding a flattening filter in a LIAC applicator, solving a clinical practical problem that authors have faced. It has been clearly demonstrated that it is possible to construct and add a filter with a relatively simple configuration able to flatten the beam delivered by the Sordina LIAC HWL, studying the implications both on the clinical beam and above all, on the peripheral dose, which is critical in this particular accelerator model. Prior to its use in clinical practice further studies are required focusing on more refined technical solutions fully compatible with the integrity of the applicator, including its sterilization.

Although this protocol should be repeated for any other applicator size and energy beam combination, the information gathered in this case offers a validated protocol that will facilitate any further development in that direction.

5. Conclusions

A flattening filter has been designed to homogenize the LIAC HWL 12 MeV energy beam with applicator of A10. To design it, a set of MC simulations were carried out to predict the dose distribution and beam flatness. MC methods allow to design a filter varying all possible parameters before its manufacturing saving both, time and resources. Then, the final designed filter was manufactured using a 3D printer. Experimental validation concludes that the beam flatness has improved from 5.9% to 1.6% with no significant (less than 2.6% and well within the maximum value provided by the manufacturer) increase of the peripheral dose. Moreover, PDD, beam profiles, absolute and peripheral dose have also been measured to demonstrate the effectiveness of the filter addition in the applicator. The study of the impact of the filter addition in the clinical beam shows a reduction of 16% of the dose and a reduction of 1.1 mm in the D_{50} of the PDD in comparison with the original configuration, which should be considered for future usage in the clinical practice.

Author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giuseppe Felici reports a relationship with S.I.T. Sordina IORT Technologies S.p.A. that includes: employment.

Data availability

The data that has been used is confidential.

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