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EXECUTIVE SUMMARY OF THE THESIS

Monte Carlo study of clinical treatment conditions provided by NOVAC 11 IOERT accelerator

TESI MAGISTRALE IN NUCLEAR ENGINEERING – INGEGNERIA NUCLEARE

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1. Introduction

Nowadays radiotherapy techniques have been established as therapies for the treatment of tumors. Radiotherapy makes use of ionizing radiation to affect the tumoral cells. The aim of radiotherapy is to give dose to the tumor trying to spare the surrounding healthy tissues.

One of the most recent radiotherapy techniques is IOERT (Intra Operative Electron Radiotherapy) which uses a beam of MeV electrons to treat semi-deep tumors in the range of a few centimeters. The peculiarity of this treatment is that it can be performed directly in the operating room through mobile linear accelerators, giving the possibility to use, in addition to the classic devices such as bolus and radiation protection vests, also radiation shielding disks [1].

The goal of this thesis is to perform a dosimetric characterization of the Novac-11 accelerator through a Monte Carlo approach. First of all, the Monte Carlo code was validated through the experimental measurements performed at the ASST Papa Giovanni XXIII (Bergamo) hospital in the context of the characterization of the Novac-11 LINAC for a delivery with a nominal energy of 10 MeV and with three different circular applicators of 10 cm, 6 cm and 5 cm in diameter.

Subsequently, the dosimetric variations induced by the presence of the various devices along the beam axis were studied.

2. IORT

IORT (Intra Operative Radiotherapy Treatment) is a radiotherapy treatment performed with the aim of sterilizing the tumor bed, previously surgically removed, to reduce the possible reoccurrence of local disease [1].

It is generally performed using an electron beam [1]. In this case the treatment is called IOERT. This kind of LINAC presents applicators in PMMA of various geometries. In the ASST Papa Giovanni XXIII (Bergamo) the most used are circular applicators of 10 cm, 6 cm and 5 cm in diameter. Being made in PMMA, the applicators let the leakage of some primary electron and generate an X-rays bremsstrahlung component.

The treatment is generally performed with an open wound such that it is necessary to obtain a "step" beam in order to give the right amount of dose to the tumor bed and spare the surrounding healthy tissues, which is why an electron beam is preferred. In fact, a treatment with electrons provides an irradiation field with the following characteristics:

- Sufficiently extended to cover the entire target (the dose in the target area must have a value equal to at least 90% of the prescribed dose)
- Modest penumbra (region in which the dose value, normalized to the maximum value, is between 20% and 80%)
- Low dose on the surface
- Rapid descent of the distal dose

3. Monte Carlo method

The Monte Carlo method exploits computational approach based on random sampling to obtain approximate numerical results of mathematical problems which, having many degrees of freedom, cannot be solved analytically. In particular, the Monte Carlo method refers to a family of methods used to approach problems of various through simulations. These always have the same approach:

- Definition of the input domain and its probability density.
- Generation of a random input through various sampling methods.
- Execution of a cycle of simulations through a stochastic model.
- Mediation of the results of the single simulations to obtain an expectation value of the system.
- Estimation of the statistical error (variance).
- Applications of variance reduction techniques (if necessary).

The applications of these methods are various and concern many fields of medical physics such as: radiological diagnostics, radiotherapy, nuclear medicine and radiation protection.

The application of the Monte Carlo method in the field of particle physics is essentially based on the simulation of the transport of the primary particles, i.e. the electrons produced by the accelerator, and the events generated by them for the determination of observables which cannot generally be obtained analytically.

One of the advantages of using the Monte Carlo method in medical physics is the possibility of studying the variation of the output of our system with respect to the setup of the analyzed problem without having to perform an experimental measurement. To do that it is necessary to previously validate the code in reference setup.

In this work the validation concerned the determination of the energy spectrum of the electrons produced by the Novac-11 accelerator, ie the input domain and the probability density of this, with the goal of reproducing the dose deposition profile along the clinical axis obtained experimentally under reference condition.

After such code validation it was observed how the dose distribution in a water phantom varied in the case of the introduction of radiation shielding disks posterior to the region corresponding to the therapeutic target and the effects of other devices.

The simulations were performed through the Monte Carlo code FLUKA.

4. Gamma Test

Gamma Test is a comparison method for dose profile that takes into account the contribution of high gradient areas [2]. This method is based on the measurement of a Gamma Value for each point of the reference profile with respect to all points of the compared profile. If this parameter is less than 1, the point studied is in accordance with the chosen parameters, otherwise it is not.

The Gamma Value is evaluated as follows:

$$\gamma = \sqrt{\frac{(r_i - r_0)^2}{\Delta r^2} + \frac{(D_i - D_0)^2}{\Delta D^2}}$$

Where:

- γ is Gamma Value (γ>1 the points are not in agreement, γ<1 the points are in agreement).
- r_i is the geometric coordinate of the profile to be compared.
- r_0 is the geometric coordinate of the reference profile.
- D_i is the dose of the profile to be compared evaluated in ri.
- D_0 is the dose of the reference profile evaluated in r0.
- ΔD is the "dose-difference" parameter.
- Δr is the "distance-to-agreement" parameter (DTA).

The two parameters, ΔD and Δr, are chosen arbitrarily and respectively indicate the maximum value of difference in dose and spatial displacement that can be present between two points so that they are considered to be in agreement. In this work we decide to set at 2% / 2mm. Two distributions are said to be in agreement if 95% of the points presents γ <1.

5. Validation

The validation process focused on the description of the energy spectrum of the source. In fact, once the physical and geometric simulation parameters that best described the real case were set, it has been necessary to modify the energy spectrum of the electrons in order to obtain a good correlation between the experimental PDD and that obtained through the simulation. It must be emphasized that the simulated irradiations have a nominal energy delivered of 10 MeV, which does not correspond to the fact that the accelerator emits a monoenergetic beam at 10 MeV [1].

The validation process began by finding the energy of a monoenergetic beam that would return the best approximation of the R_{50}. The use of symmetric, Gaussian and rectangular, energy distributions was then investigated. Especially the first gave excellent approximations either in the surface component of the curve or in the deep one as the standard deviation varied, but never in both with the same standard deviation. It was therefore decided to implement an asymmetrical distribution with a low energy component.

The construction of the histograms was done starting from a skew normal distribution. In particular, each histogram, 1 MeV wide, will have a height equal to the average of the skew normal distribution in that energy range.

The skew normal distribution that yielded the best correlation was found to be described by a mean of 12, a standard deviation of 3.5, and an asymmetry factor of -100. The histogram obtained is reported in *Figure 1*.

Three different circular applicators with diameters 10 cm, 6 cm and 5 cm are validated for a delivery with the nominal energy of 10 MeV, respecting the Gamma Test with parameters 2% / 2mm.

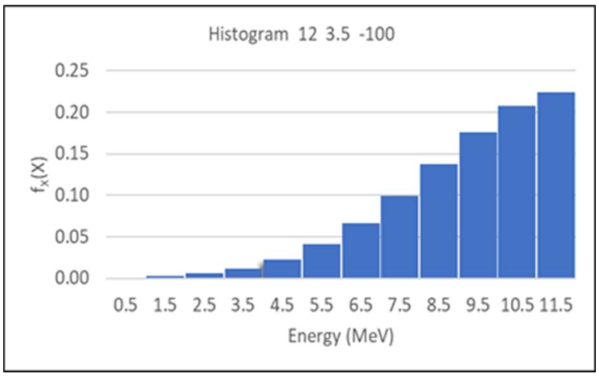

Figure 1 Histogram used to describe the energy distribution of the electron source.

6. Dosimetric characterization

In the next paragraphs the main results about the dosimetric characterization of the IORT devices are shown.

6.1 Characterization of radiation shielding disks

The radiation shielding disks have the task of limiting the dose to the tissues posterior to the target. The use of a disk of high-Z material imposes a great shielding factor of the posterior tissues.

However this kind of disks generates an important backscattering component that must be shielded with an additional low-Z filter placed between the target and the high Z disk [3, 4]. The manufacturer of Novac-11 (Sordina S.p.A.) suggests the use of a 3 mm thick steel disk (AISI 316L) coupled with a 5 mm thick polyether-ether-ketone (PEEK plastic) disk. At the ASST Papa Giovanni XXIII hospital (Bergamo), a lead and aluminum disks, both with a thickness of 5 mm, are also used as an alternative. So this two different two-layers disks were simulated for target of 1 cm, 1.5 cm, 2 cm, 2.5 cm and 3 cm.

From a clinical point of view, the PEEK-aluminum disk certainly provides greater safety. Indeed, it does not substantially change the PDD in target region, providing, especially for deep targets, a good shielding capacity of healthy tissues. The planning of an IOERT treatment, in which the use of a PEEK-aluminum disk is used, does not provide for the risk of exceeding 105% of the nominal prescribed dose.

On the other hand, the aluminum-lead disk has excellent shielding performance for any target. The greatest difference in terms of shielding between the two disks is observed with a target of 1 cm, where the aluminum-lead disk saves the patient's tissues more than 4 Gy compared to the PEEK-steel disk for a delivered treatment in one session. However, the lead aluminum disk presents some criticalities in the target region. Presenting a more important backscattering contribution, an excess dose is observed compared to 105% of the nominal energy. The electron and photon spectrum evaluated after the disks confirmed the greater ability to shield the radiation of the Al-Pb disk.

During the characterization of the radiation shielding disk some parameters have been evaluated, the most relevant are the Backscattering Factor (BF) and the Trasmission Factor (TF).

The Backscattering Factor describes the percentage change in dose between the condition in the presence of the disk and the reference condition at each depth z.

$$BF(z) = \frac{D_{disk,i}(z)}{D_{rif,i}(z)}\%$$

The Transmission Factor describes the percentage change in dose between the condition in the presence of the disk and the reference condition. It is evaluated in the first point after the disk.

$$TF = \frac{D_{disk}}{D_{rif}}\%$$

In general it is possible to conclude that the dosimetric effects generated by the presence of the radiation shielding disks does not depend significantly on the size of the applicator, since the numerical values of any parameters obtained are very similar for all the applicators if the disk used is the same.

In the following table are reported the numerical results for BF and TF evaluated for a 10 cm circular applicator. BF is evaluated 0.5 mm before the dimension of the target, where the backscattering phenomenon is most observed. The other two applicator present similar numerical result.

Target	1 cm	1.5 cm	2 cm	2.5 cm	3 cm
Al-Pb disk – 10 cm circular applicator					
BF	110.00%±0.59%	107.93%±0.51%	107.78%±0.57%	109.03%±0.58%	108.14%±0.70%
TF	0.77%±0.04%	0.60%±0.04%	0.42%±0.05%	0.45%±0.06%	0.46%±0.10%
PEEK-Ac disk – 10 cm circular applicator					
BF	104.61%±0.58%	102.97%±0.53%	102.58%±0.64%	102.31%±0.79%	99.04%±0.62%
TF	25.19%±0.09%	11.71%±0.16%	4.25%±0.11%	1.22%±0.08%	0.52%±0.11%

Table 1 Numerical results of radiation shielding disk for A10

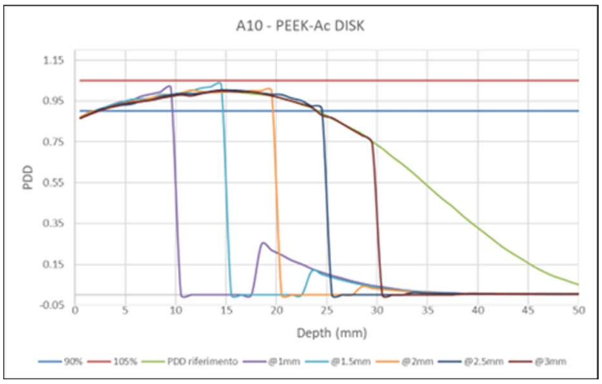

Figure 3 PDD (Percentage Profile Dose curve) of a 10 cm circular applicator, at a nominal energy of 10 MeV, in presence of PEEK-Ac disk for different sized target.

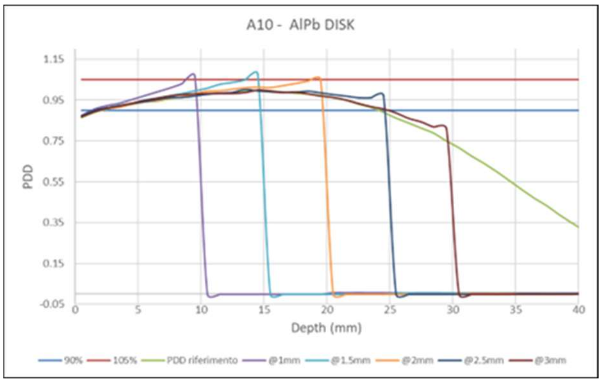

Figure 2 PDD (Percentage Profile Dose curve) of a 10 cm circular applicator, at a nominal energy of 10 MeV, in presence of Al-Pb disk for different sized target.

6.2 Characterization of radiation protection vests

On the market there are various radiation protection vests dedicated to health workers. In the IORT field, it was decided to adapt them to preserve the patient's skin from any diffuse radiation emitted by the applicator. Two devices were simulated: one consisting of a 0.5 mm lead layer and another consisting of an equivalent water layer 1 cm thick, representing a RT bolus. However, it must be noted that a dose component at the surface is due to radiation that actually reaches the target but is subsequently scattered (phantom scatter effect). It is therefore not shieldable by superficial devices.

The dose was evaluated on a radial coordinate perpendicular to the clinical axis of the beam (0; 0; Z) to the surface of the phantom. The cylindrical IORT irradiation geometry results in perfect azimuthal symmetry of skin exposure, of progressively lower intensity as the radial distance from applicator wall increases. In the absence of any radiation protection vest, it was observed that the skin receives a value of 2% -3% of the maximum dose in the first point closest to the applicator, moving away from the applicator the dose decreases. In general radiation protections vests save about 25% of the dose to the skin. In particular, the water equivalent bolus has a greater shielding capacity than the lead apron.

The Transmission Factor, evaluated as the dose ratio in the presence of the radiation protection vests and in reference conditions, shows fairly high values for both devices between 60% and 80% near the applicator. Moving away from the applicator, the TF value decreases.

The analysis of the energy spectra of electrons and photons between the bolus and the water phantom confirm that the water equivalent bolus has a better ability to attenuate the radiation, especially reducing the high energy component of electrons.

As example skin dose (expressed as normalized dose respect to the build up dose) and the Transmission Factor are shown for a circular applicator with 10 cm diameter. The other two applicators present comparable trends.

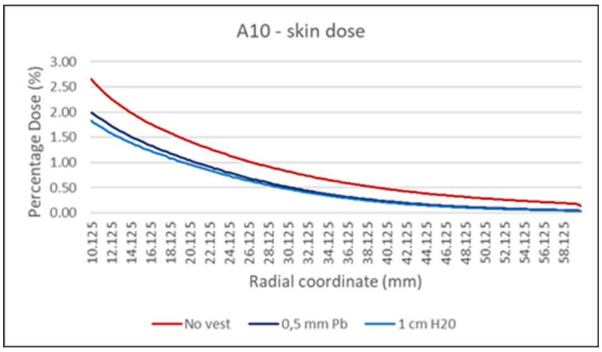

Figure 4 Normalized skin dose for 10 cm circular applicator

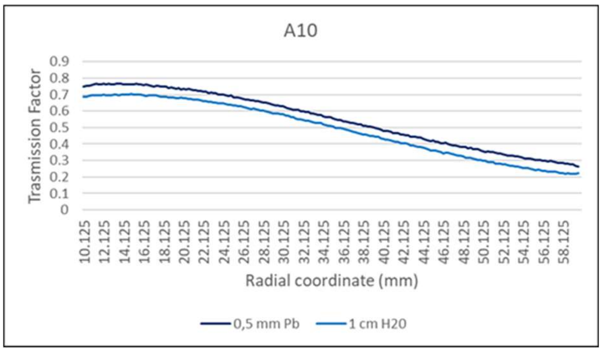

Figure 5 Trasmission Factor for the two different radiation protection vests

6.3 Characterization of applicator bolus

The bolus is used to avoid herniation tissue phenomena and to uniform the irradiation field transversally for any applicator and for any nominal energy.

The aim of the simulations performed with the bolus was to verify that PMMA, a water-equivalent material, does not modify the shape of the PDD. Only a rigid leftward translation of the PDD proportional to the bolus thickness is expected.

It was decided to simulate the use of a 10 mm thick bolus with a 10 cm circular applicator and with a nominal energy of 10 MeV. The results confirm what was expected. In fact, a rigid translation of 10 millimeters is observed, precisely equal to the thickness of the bolus, of the PDD with bolus compared to that in reference conditions.

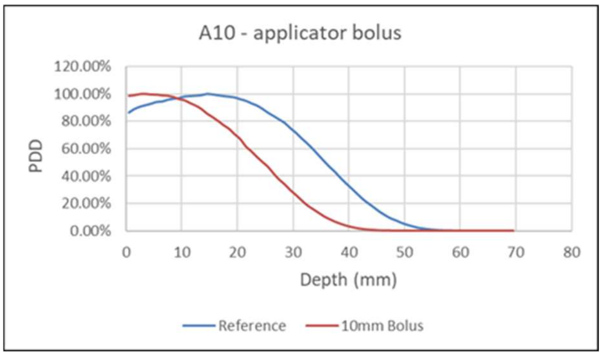

Figure 6 PDD (Percentage Profile Dose curve) of a 10 cm circular applicator, at a nominal energy of 10 MeV with a 10 mm applicator

7. Conclusions

The thesis proposes a complete dosimetric characterization of an IORT treatment performed with a LINAC Novac-11 and the various associated devices. The results obtained are in agreement with works already present in the literature, both as regards the validation process and the use of radiation shielding disks [3, 4, 5].

The main result obtained underlines the usefulness of radiation shielding disks in preserving healthy tissues posterior to the target. In addition, the total amount of dose received by the skin around the applicator was evaluated and the positive effect induced by the use of two different radiation protection vests was quantified. Finally, the effect of the presence of a bolus applicator was evaluated

The thesis also presents the energy spectra evaluated at the base of the phantom and after the radiation shielding disks. These, even if not validated, confirm the results obtained and are in agreement with similar works present in the literature [5].

Finally, in the last chapter of the thesis, some changes to the thickness of the disks are presented in order to reduce the limits of these emerged from the characterization. This last part acts as a starting point for future works.

References

[1] Andreoli, S., Ciabattoni, A., de Angelis, C., Leonardi, M. C., Menegotti, L., Pimpinella, M., & Rosi, A. (2021). Assicurazione di qualità nella radioterapia intraoperatoria Aggiornamento del Rapporto ISTISAN 03/1.

[2] Low, D. A., & Dempsey, J. F. (2003). Evaluation of the gamma dose distribution comparison method. Medical Physics, 30(9), 2455–2464.

[3] H. Alhamadaa, S. Simona,b, C. Philippsonb, C. Vandekerkhoveb, Y. Jouranib, N. Paulya, D. Van Gestelb, N. Reynaertb (2020). Monte Carlo dose calculations of shielding disks with different material combinations in intraoperative electron radiation therapy (IOERT). Cancer/Radiothérapie 24 (2020) 128–134

[4] Hamid Reza Baghani, Mostafa Robatjazi, Seyed Rabi Mahdavi (2020). Comparing the performance of some dedicated radioprotection disks in breast intraoperative electron radiotherapy: a Monte Carlo study. Radiation and Environmental Biophysics (2020) 59:265–281

[5] Righi S, Karaj E, Felici G, Di Martino F. Dosimetric characteristics of electron beams produced by two mobile accelerators, NOVAC7 and LIAC, for intraoperative radiation therapy through Monte Carlo simulation. J of ACMP 2013;14(1):6-18.