CHALLENGES IN RADIOTHERAPY PLANNING: DOSE VERIFICATION IN THE VICINITY OF THE BORDER OF TISSUE-PROSTHESIS MEDIUM*

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The success or failure of radiotherapy largely depends on the accuracy with which the dose will be delivered to a specific volume in the patient's body. One of the problems associated with radiotherapy planning for patients with endoprostheses is the inaccuracy of the algorithm calculating the dose distribution in the treatment planning system for the area in the vicinity of the border of tissue–prosthesis medium. The aim of this study is verification of a planned dose on the border of hip prosthesis–acetabulum surface. At the examined energy — 6 MV — a dose results in decrease at the border of the medium, to achieve up to 10%. To verify this hypothesis, a water-filled phantom (soft tissue equivalent) was used with bone fragments (imitating hip joint) and metallic elements (hip joint endoprostheses) placed in a working stand. On acetabulum surface, thermoluminescent microdosimeters (TLD) based on lithium fluoride (LiF) was placed. The irradiation by medical linear accelerator was performed. The planned dose is higher compared with measured dose by approx. 9.8% (1.112 *vs.* 1.003 Gy for 2 Gy of fraction dose). It was confirmed that the treatment planning system overestimates the dose on the surface of acetabulum.

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1. Introduction

Besides a successful treatment, the main objective of radiotherapy is assessment of high-energy ionizing radiation in an oncologic treatment. Radiation therapy is based on a general assumption of the most effective tumor growth suppression with the minimum possible damage of healthy tissues located in its vicinity (OAR — Organs At Risk).

The stage of a disease is one of the most important factors determining the treatment strategy (radical treatment — complete elimination of the cancer, palliative treatment — reducing the soreness associated with the disease progress by its alleviation), and selected treatment techniques (*e.g.* radiosurgery, teleradiotherapy, brachytherapy). The effectiveness, as well as the success of the entire therapeutic process depend on the possibility of administration a sufficiently large dose to achieve a full local control over the tumor (complete destruction of cancer cells) and avoid complications in healthy tissues. Therefore, the often used parameter that includes models describing cellular responses to ionizing radiation (associated with the likelihood of cell lethal damage), corrected for practical principles governing the radiotherapy process, is the value of the probability of local cure of the tumor and the occurrence of complications in healthy tissues depending on the administered dose (change in this value up to 5% may result in 25% changes in the healing likelihood) [1]. Therefore, it is extremely important to achieve sufficiently high precision and uniformity of the delivered dose to the entire tumor volume. This approach involves both the exact determination of the absolute dose value within the beam, the repetitive setting of the radiation source (*e.g.* accelerator), as well as the delivery of the dose to a specific volume in the patient's body — reproducible arrangement in subsequent therapeutic sessions. Clinical Target Volume (CTV) is the total volume of the tumor plus the adjacent volume in which the cancer can spread. The PTV (Planning Target Volume) area is determined by adding the appropriate margin size to the CTV area (*e.g.* 5–10 mm from the CTV border surface). Margin depends on the type of cancer, location, organ mobility (specific and internal mobility), uncertainty in the patient's positioning and the uncertainty of therapeutic equipment. The human body is composed of tissues that are heterogeneous in terms of their density (bones, lungs, teeth, muscles *etc.*) [2]. In a number of patients, besides natural heterogeneous structures, the presence of artificial structures and components, *e.g.* hip, leg and shoulder prostheses, surgical rods, stents and dental fillings should be taken into account.

One of the problems associated with planning radiation therapy for patients with endoprostheses (mainly hip joints) is the inaccuracy of the algorithm that calculates the dose distribution in the treatment planning system for the area directly behind the prosthesis — on the border between tissue

(acetabulum)–prosthesis. There are two main phenomena caused by high-density metal element: beam hardening and secondary build-up of the dose. They are not taken into account by the algorithm in the treatment planning system.

2. Aim

The aim of this work is to measure the actual dose deposited on the border of mediums significantly differing in density (atomic number Z) and comparing its values with those determined using algorithms implemented into the treatment planning system. This verification will help carrying out treatment plans for patients after implantation of hip endoprosthesis and in assessing the potential effects of such a plan.

3. Materials and methods

All irradiations were carried out at the Oncology Center, Institute of Maria Skłodowska-Curie Memorial Institute, Kraków Branch, at the unique accelerator (Varian Medical Systems) using 6 MV photon energy. The irradiation was carried out in the VMAT (Volumetric Modulated Arc Therapy) technique, dynamic rotary arc technique using the rotation of the therapeutic head of the apparatus with simultaneous modulation of the intensity of the beam during rotation related to volume modulation. Treatment plans were prepared and calculated in the TPS (Treatment Planning System) Varian Eclipse, version 11, using the AAA (Anisotropic Analytical Algorithm) version 10.0.28.

To verify the dose at the border between the bone tissue and endoprosthesis surface, a phantom was built corresponding to the shape of the real body of the patient undergoing radiation in the selected anatomical area: pelvis, hip joint endoprosthesis, acetabulum together with the head and the femoral neck.

An artificial pelvis (PVC, HU = 1300–1500, according to data obtained from a CT scanner) was selected as the material for the study. Artificial pelvis finally turned out to be free of defects that were noticed in the previously selected materials such as: dried human bone (from the archaeological resources of the Jagiellonian University) and pork bones. Both materials were characterized by inadequate density and/or the inability to reuse due to material deterioration. In addition, the PVC was easy to process and prepare places for thermoluminescent detectors (TLD). Aesculap endoprosthesis (Screw Socket S.C. — NH448T — ISOTANF — alloy type (Ti6Al4V/ISO 5832-3)) with diameter of 48 mm was used for the study. This alloy is used in bone surgery in the $\alpha + \beta$ biphasic structure, also known under the trade name Prorasul — 64WF. A cement-free mandrel was also used (Aesculap — NC087K — ISODUR — alloy type (CoCrMo/ISO 5832-12)). Both the

phantoms, the pelvic support stand and the endoprosthesis in a repetitive position, used for irradiation, were entirely created from tissue-like material Poly(methyl methacrylate) (PMMA), its interior was filled with water (Fig. 1).

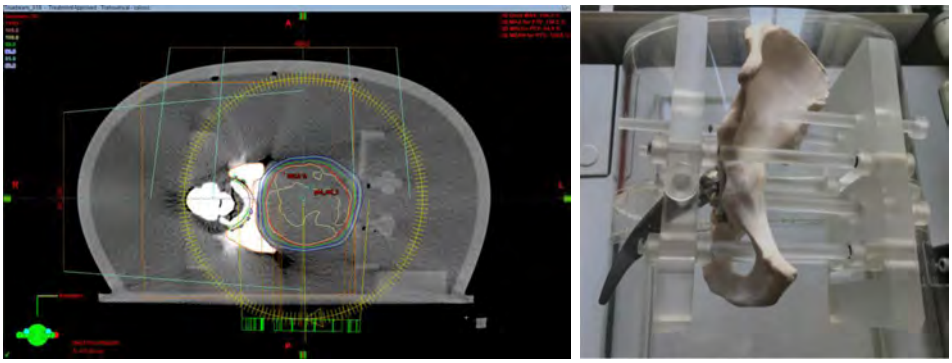

Fig. 1. Left — tomographic transversal view through the phantom filled with water with a tripod, hip bone, prosthesis and detectors inside, during the treatment planning process. Right — view of the phantom [own materials].

After assembling all phantom elements, thermoluminescent detectors (TLD) type MTS-N were placed on the surface connecting the prosthesis with the bone, in previously prepared cavities [3, 4]. All 64 detectors with a diameter of $\phi = 4.5$ mm, thickness ~ 0.7 mm and a mass of 35 ± 0.5 mg were selected and used to verify the actual dose deposited in the bone tissue at the border of two mediums [5, 6]. To protect the detectors against falling out, they were glued with kapton tape slightly contaminating the surface of the detectors with glue. The phantom prepared in this way was transported to the medical accelerator bunker, placed in a repetitive position on the therapy table (in relation to the lasers in the bunker) and filled with water. Then Image Guided Radiation Therapy was performed with 2D–2D MV images. After correction of couch position, the phantom was irradiated in accordance with the previously prepared "treatment plan" — made in the VMAT technique, adequate as in the case of standard irradiation of real patients. After irradiation, the water was pumped out of the phantom and the detectors were allowed to dry.

Each time after the irradiation process was completed, the dose was evaluated using a Lexygsmart TL/OLS reader. Dose calibration was performed for each batch of detectors (for 2 Gy, 1 Gy, 0.5 Gy, and background dose) on the same apparatus where the phantom measurement was performed. Eight series of 6 MV photon irradiation were performed. In total, 512 TLD detectors were irradiated (additionally 32 detectors used for dose

calibration). At each series, the detectors were numbered and embedded in specially prepared wells. Then, for a given well set, the dose was averaged and compared with the result obtained from the treatment planning system (TPS) (Fig. 2).

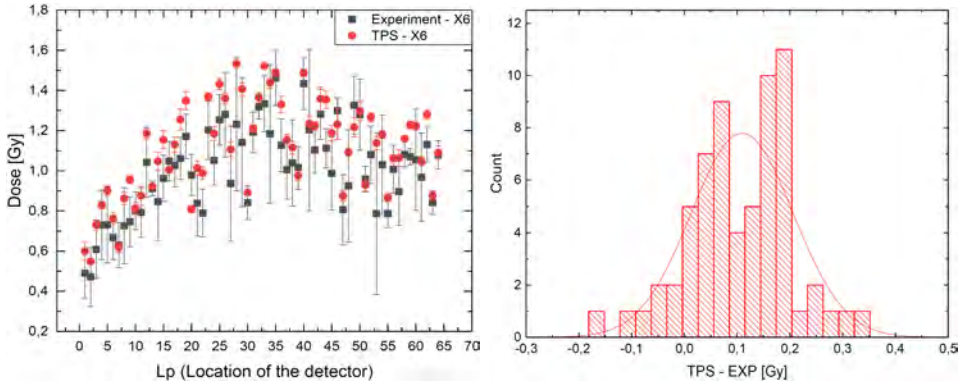

Fig. 2. Dose verification calculated using TPS (Eclipse, AAA) measured by TLD detectors. The graph on the left presents the doses for individual nests on the border of prosthesis/bone, while the histogram on the right represents the distribution of differences in calculated and determined doses along with matching the normal distribution to the results obtained.

4. Results and discussion

Measured values were lower then planned in TPS. For measurement, $\text{Mean}_{\text{Normal}} = 0.109 \pm 0.097$ Gy. Values calculated by the TPS are higher by 9.83% in mean.

Due to the high energy of ionizing radiation used in RT, the dose delivered during the therapeutic session may change significantly compared to the originally assumed [7, 8]. As shown by our experiments, this change may reach up to 10% of the lower value for commonly used energy (6 MV) in dynamic techniques, at the border of 2 mediums with different density. This change is associated with such phenomena as: hardening of the beam, loss of electron equilibrium, radiation scattering, secondary build up, which cause lowering the dose at the medium border — by even more than 20% according to the Monte Carlo simulation predictions [9–12]. Such a large change in the deposited energy in the tissues of treated patients can lead to skeletal changes (leading to hip fractures), weakening of implant fixation or even necrosis.

In summary, our research shows a significant decrease of radiation intensity after passing through the endoprosthesis-building material, which may undoubtedly have an impact on the distribution of the dose outside the

implant area (*e.g.* reduction of the average dose in the small pelvis area). In the case of low-energy radiation (with a nominal value of 6 MV), which was used for the needs of this work, the result is favourable because the bone in the immediate vicinity will not receive an increased dose — the risk of necrosis will decrease. Another effect is related to the hardening of the radiation beam — the range of used radiation increases, while its ability to transfer energy decreases, which will result in the above-mentioned phenomenon. Therefore, it seems that thanks to a better understanding of the dose distribution, those responsible for preparing a treatment plan can make more informed decisions about treatment design in patients with high-density prosthetic materials, and thus, improve patient outcomes.

REFERENCES

[1] D.D. Chamberlain, J.B. Yu, R.H. Decker, *Kompendium Radioterapii Onkologicznej*, MedPharm Polska, Wydanie I Polskie, 2018, ISBN:978-83-7846-099-2.

[2] T. Landberg *et al.*, Report 50, Journal of the International Commission on Radiation Units and Measurements, Volume os26, Issue 1, September 1, 1993, Page NP, DOI:10.1093/jicru/os26.1.Report50

[3] B. Obryk, Raport Nr 2045/D — Opracowanie metody pomiaru wysokich dawek promieniowania jonizującego z zastosowaniem wysokoczułych detektorów termoluminescencyjnych LiF:Mg,Cu,P, www.ifj.edu.pl/badania/publikacje/raporty/2010/2045.pdf?lang=pl, Kraków 2010.

[4] B. Obryk, P. Bilski, Thermoluminescent dosimetry service at the IFJ Kraków, Seminarium RADMON (Radiation Monitoring Working Group at CERN), 2007, http://indico.cern.ch/conferenceDisplay.py?confId=12735

[5] P. Wesolowska *et al.*, *Acta Oncol.* **58**, 1731 (2019).

[6] K. Chełmiński, W. Bulski, *Rep. Pract. Oncol. Radiother.* **15**, 40 (2010).

[7] A. Mesbahi, F.S. Nejad, *Radiat. Med.* **25**, 529 (2007).

[8] K. Mohammadi *et al.*, *J. Cancer. Res. Ther.* **13**, 501 (2017).

[9] C. Reft *et al.*, *Med. Phys.* **30**, 1162 (2003).

[10] S. Catli, G. Tanir, *Med. Dosim.* **38**, 332 (2013).

[11] S.Y. Lin *et al.*, *Appl. Radiat. Isotopes.* **57**, 17 (2002).

[12] D. Paulu, P. Alaei, *J. Appl. Clin. Med. Phys.* **18**, 9 (2017).