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Dosimetry

Dosimetry auditing procedure with alanine dosimeters for light ion beam therapy

Alexander Ableitinger [a,*], Stanislav Vatnitsky [a], Rochus Herrmann [d,e], Niels Bassler [d,e], Hugo Palmans [f], Peter Sharpe [f], Swantje Ecker [h], Naved Chaudhri [h], Oliver Jäkel [g,h], Dietmar Georg [b,c]

[a] EBG MedAustron, Wiener Neustadt; [b] Department of Radiooncology, Medical University of Vienna/AKH Vienna; [c] Christian Doppler Laboratory for Medical Radiation Research for Radiation Oncology, Medical University of Vienna, Austria; [d] Department of Physics and Astronomy, Aarhus University; [e] Department of Experimental Clinical Oncology, Aarhus University Hospital, Denmark; [f] National Physical Laboratory, Teddington, United Kingdom; [g] Division of Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ) Heidelberg; and [h] Heidelberg Ion-Beam Therapy Center (HIT), Heidelberg University Hospital, Germany

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Background and purpose: In the next few years the number of facilities providing ion beam therapy with scanning beams will increase. An auditing process based on an end-to-end test (including CT imaging, planning and dose delivery) could help new ion therapy centres to validate their entire logistic chain of radiation delivery. An end-to-end procedure was designed and tested in both scanned proton and carbon ion beams, which may also serve as a dosimetric credentialing procedure for clinical trials in the future. The developed procedure is focused only on physical dose delivery and the validation of the biological dose is out of scope of the current work.

Materials and methods: The audit procedure was based on a homogeneous phantom that mimics the dimension of a head ($20 \times 20 \times 21$ cm^3). The phantom can be loaded either with an ionisation chamber or 20 alanine dosimeters plus 2 radiochromic EBT films. Dose verification aimed at measuring a dose of 10 Gy homogeneously delivered to a virtual-target volume of $8 \times 8 \times 12$ cm^3. In order to interpret the readout of the irradiated alanine dosimeters additional Monte Carlo simulations were performed to calculate the energy dependent detector response of the particle fluence in the alanine detector. A pilot run was performed with protons and carbon ions at the Heidelberg Ion Therapy facility (HIT).

Results: The mean difference of the absolute physical dose measured with the alanine dosimeters compared with the expected dose from the treatment planning system was $-2.4 \pm 0.9\%$ (1σ) for protons and $-2.2 \pm 1.1\%$ (1σ) for carbon ions. The measurements performed with the ionisation chamber indicate this slight underdosage with a dose difference of -1.7% for protons and -1.0% for carbon ions. The profiles measured by radiochromic films showed an acceptable homogeneity of about 3%.

Conclusions: Alanine dosimeters are suitable detectors for dosimetry audits in ion beam therapy and the presented end-to-end test is feasible. If further studies show similar results, this dosimetric audit could be implemented as a credentialing procedure for clinical proton and carbon beam delivery.

If conventional radiotherapy institutions are planning to participate in clinical trials, dosimetric audits are considered mandatory and may serve as a credentialing procedure. The purpose of these auditing procedures is to achieve a sufficient dosimetric accuracy among the participating radiotherapy centres and to ensure the comparability and reproducibility of clinical studies and treatment protocols. Different audits have been established for clinical high-energy photon and electron beams [1–4]. These dosimetric procedures are predominantly based on thermo-luminescent dosimeter (TLD) that needs to be irradiated in reference and non-reference conditions in a homogeneous phantom. As far as non-reference conditions are concerned, audits are directed towards beam data implementation in treatment planning systems and their dose calculation accuracy. Highly advanced auditing procedures, an end-to-end test with homogeneous or heterogeneous anthropomorphic phantoms, have been established by the International Atomic Energy Agency (IAEA) or the Radiological Physics Center (RPC). The purpose of such an end-to-end test is to confirm that the entire logistic chain of radiation treatment starting from CT imaging, treatment planning, monitor calibration and beam delivery is operable and leads to the desired results with sufficient accuracy. These tests are mainly focusing on advanced treatment techniques [4–8]. Especially for new treatment techniques implemented in a centre and clinical trials these end-to-end tests can help to detect and eliminate any possible systematic error occurring in the treatment chain or dosimetry process, respectively.

* Corresponding author. Address: EBG MedAustron, Marie Curie-Straße 5, 2700 Wiener Neustadt, Austria.
E-mail address: alexander.ableitinger@medaustron.at (A. Ableitinger).

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In the framework of the ULICE project (Union of Light Ion Centres in Europe) a questionnaire has been sent to existing proton and ion beam facilities in Europe to evaluate the demand on a dosimetry intercomparison for ion beam therapy. The received feedback revealed clearly the need for a dosimetric procedure, which is motivated by the implementation of scanning beam techniques. The procedure of reference dosimetry and consequently the calibration of dose monitors in scanning beams is usually defined by the output of the treatment planning system (TPS) [9]. Therefore the calibration may include several additional steps compared to the dose monitor calibration of clinical beams produced with the passive beam delivery technology. The features of scanning beam delivery complicate dosimetric intercomparison between facilities and require specific procedures. The most efficient solution for the dosimetry intercomparison of scanning beam delivery systems is to use end-to-end test based auditing procedures. Such intercomparisons would also contribute to a dosimetric harmonisation among ion beam therapy centres, which is currently challenged by the lack of international and national primary dose standards for protons and heavier ion beams [10–12]. But compared to dosimetric auditing procedures for conventional photon and electron beam therapy, additional dose rate and linear energy transfer (LET) effects of the scanning beam might be present and need to be taken into account when analysing the detector response.

The current paper describes a feasibility study of a dosimetric end-to-end test developed for scanned protons and heavy ions. The procedure was based on a solid plastic phantom and dosimetric measurements with an ionisation chamber and alanine dosimeters. Alanine detectors were successfully used at the National Physical Laboratory (NPL) for measurements in proton beams and were proposed as detectors for postal dosimetry intercomparisons [13], although the response of these detectors depends on LET and requires therefore specific correction factors.

The developed procedure was focused only on physical dose delivery and the validation of the biological dose is out of scope of this work. Institutions providing carbon beam therapy in Europe and Japan are using different biological models that require specific effort in comparing biological dosimetry. Therefore the comparison of physical dose in scanning ion beam delivery can be considered as the first step in setting up intercomparison procedures.

To test the feasibility of the designed audit a pilot run was performed at the Heidelberg Ion Therapy facility (HIT) with protons and carbon ions. Nevertheless the presented procedure is not facility specific and covers typical steps of ion beam planning and modulated scanning beam delivery technology.

Materials and methods

The purpose of the end-to-end test was to verify that the whole logistical chain of treatment delivery is operable and leads to the desired results with sufficient accuracy. During the testing the phantom was moving through the workflow as a real patient to simulate the clinical procedure.

Phantom

The phantom used for the auditing procedure was designed in such way that its dimensions represent a head phantom. Seven plates, each with a size of $20 \times 20 \times 3$ cm^3, were stacked together to form a 21 cm long phantom. The schematic views are given in Fig. 1(a) and (b). The material of the phantom is polystyrene which has a mass density close to water. The water equivalent thickness (WET) of the phantom material – the thickness of water that results for a charged particle beam in the same integral loss of energy due to the electronic stopping power as the thickness of the tested material – was measured at Gantry 1 at the Proton Therapy Centre at the Paul Scherrer Institute (PSI). The measurement was performed with a large area ionisation chamber integrated in a daily check phantom. A 3 cm thick block of the material was placed onto the daily check phantom in a 160 MeV monoenergetic proton beam. From comparing the ranges of the depth dose curves measured with and without the block, a WET of the Phantom material equal to 1.04 g/cm^2 was derived.

The predefined virtual target volume was $8 \times 8 \times 12$ cm^3 and is indicated in red in Fig. 1(a) and (b). The phantom can host a set of 20 alanine detectors; the specific pattern of detector placement allows a good coverage of the target volume and minimises the shadowing of the detectors. Four plates, labelled as A, B, C and D, hold these dosimeters. In addition to the cavities for the alanine pellets, plates A and C were manufactured with a depression to place a radiochromic film just upon the pellets and perpendicular to the beam direction. Another plate with the same dimensions was prepared in such a way to provide space for different kind of inserts for ionisation chambers. White marking lines on the surface of the assembled phantom allow an accurate positioning during the alignment process.

Dosimeters

Three different dosimeters have been used in the phantom: alanine pellets, films and an ionisation chamber. In this study two phantom setups were used – one setup with 20 alanine dosimeters and two GafChromic EBT films and another setup with a Farmer-type chamber and dummy pellets instead of the alanine detectors to avoid inhomogeneities.

Alanine pellets

The National Physical Laboratory (NPL) provided alanine detectors for the pilot study of the dosimetric auditing procedure. The detectors are in pellet form with a nominal diameter of 5.0 mm and a thickness of about 2.3 mm. In this study a dose of 10 Gy was delivered to the alanine detectors to achieve a reproducibility of better than 0.5%. The NPL alanine detectors consist of 90.9% by weight L-α-alanine and 9.1% high melting point paraffin wax. With an averaged density of 1.23 g/cm^3 the pellets are actually close to PMMA. The dosimeters were conditioned at 55% relative humidity for ten weeks prior to use in order to reduce post-irradiation fading. After the dose deposition the irradiated dosimeters were shipped to the NPL, where they were evaluated following the standard procedure [14].

One of the challenges in alanine dosimetry with ions is the LET dependence that can be handled by Monte Carlo simulations [13,15]. The sensitivity of a detector towards a given radiation quality can be expressed by its relative effectiveness η. Here it is defined as the ratio of the dose of a reference radiation to the dose of a test radiation D_X giving the same detector response. The subscript X represents different particle types, e.g. p for a proton and ^{12}C for a carbon beam. Since NPL alanine dosimeters are calibrated in a ^{60}Co beam the relative effectiveness can be defined as:

$$\eta = \left.\frac{D_{^{60}\mathrm{Co}}}{D_X}\right|_{\mathrm{iso-response}} \quad (1)$$

where D_X denotes the dose applied by the test radiation and $D_{^{60}\mathrm{Co}}$ the dose deposited by the ^{60}Co reference radiation.

In case of a mixed radiation field with no track overlapping effects on a microscopic level, the average relative effectiveness $\bar{\eta}$ for the field, can be calculated by linear superposition of the relative effectivenesses of the individual components weighted by their dose contribution