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Out-of-field dose studies with an anthropomorphic phantom: Comparison of X-rays and particle therapy treatments

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ABSTRACT

Background and purpose: Characterization of the out-of-field dose profile following irradiation of the target with a 3D treatment plan delivered with modern techniques.
Methods: An anthropomorphic RANDO phantom was irradiated with a treatment plan designed for a simulated $5 \times 2 \times 5$ cm^3 tumor volume located in the center of the head. The experiment was repeated with all most common radiation treatment types (photons, protons and carbon ions) and delivery techniques (Intensity Modulated Radiation Therapy, passive modulation and spot scanning). The measurements were performed with active diamond detector and passive thermoluminescence (TLD) detectors to investigate the out-of-field dose both inside and outside the phantom.
Results: The highest out-of-field dose values both on the surface and inside the phantom were measured during the treatment with 25 MV photons. In the proximity of the Planned Target Volume (PTV), the lowest lateral dose profile was observed for passively modulated protons mainly because of the presence of the collimator in combination with the chosen volume shape. In the far out-of-field region (above 100 mm from the PTV), passively modulated ions were characterized by a less pronounced dose fall-off in comparison with scanned beams. Overall, the treatment with scanned carbon ions delivered the lowest dose outside the target volume.
Conclusions: For the selected PTV, the use of the collimator in proton therapy drastically reduced the dose deposited by ions or photons nearby the tumor. Scanning modulation represents the optimal technique for achieving the highest dose reduction far-out-of-field.

The advances in medical technologies have steadily increased the number of cancer survivors. In many of the successfully cured cases, the patient was exposed to radiation as part of the treatment. The extension of the life expectancy following malignant tumors posed a growing concern on the long-term effects of radiation on normal tissues and in particular on the risk of developing secondary radiation-induced cancer [1–5]. As the side effects are strongly dependent on the dose deposited outside the Planned Target Volume (PTV), investigations in the delivery techniques and treatment planning systems have to be accomplished to spare the healthy tissues during the irradiation. However, the ideal scenario where only the tumor receives 100% of the dose is unfeasible because of the unavoidable dose deposition at the beam entrance channel; moreover, the lateral scattering and production of secondary charged and uncharged particles is inevitable due to the interaction of the primary beam along its path toward the target volume (accelerator line and head, patient body). Therefore, in parallel to the optimization of the treatment procedure, investigations have been conducted to study the effect of radiation on biological systems and, combined to clinical records, to assess the risk of possible health complications following radiotherapy. A fundamental requirement to fulfill these goals is a detailed physical and dosimetrical characterization of the radiation field outside the irradiated region. The secondary fragments, especially light particles as protons and neutrons, might have enough range to deposit a non-negligible amount of energy even far away from the treatment volume. The far-out-of-field dose is rather small if compared to the in-field value but may cause a relevant damage if delivered to particularly radiosensitive organs or tissues. An extensive investigation of the dose profile following radiotherapy was conducted for several common emerging treatment modalities, studying the influence of both the type of radiation and the delivery technique. The following facilities were involved in the measurements:

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Klinikum Goethe Universität (KGU) in Frankfurt, Germany, for the irradiation with Intensity Modulated Radiation Therapy (IMRT) photons; The Svedberg Laboratory (TSL) in Uppsala, Sweden, for the irradiation with passively modulated protons; the Paul Scherrer Institute (PSI) in Villigen, Switzerland, for the irradiation with scanned protons; the Heavy Ion Medical Accelerator facility (HIMAC) at the National Institute of Radiological Sciences (NIRS), Chiba, Japan, for the irradiation with passively modulated carbon ions; the Helmholtzzentrum für Schwerionenforschung GmbH (GSI) in Darmstadt, Germany, for the irradiation with scanned carbon ions. In all the experiments, an anthropomorphic phantom (RANDO) was irradiated according to a 3D treatment plan to evaluate the dose distribution both inside and outside the PTV.

Methods and materials

Experimental setup

The target used for all irradiation was an anthropomorphic upper torso [6] (RANDO, The Phantom Laboratory, Salem, NY) built up from a human skeleton embedded in tissue-equivalent polyurethane and cut into 33 slices with a thickness of 25 mm each. A Computer Tomography (CT)-scan of the phantom head was taken prior to each experiment to produce a standard treatment plan as for a real patient. The PTV was defined as a $5 \times 2 \times 5\ \text{cm}^3$ volume placed at the center of the phantom head (slice 4, see Fig. 1).

The dose profile was measured both at the surface and inside the phantom with thermoluminescence detectors of the type TLD-700 (^{7}LiF:Mg) purchased from Thermo Fisher Scientific and a diamond detector model 60003 from PTW Freiburg, Germany.

All thermoluminescence detectors were calibrated with 662 keV photons from a ^{137}Cs source to absorbed dose in water delivered by ions and photons. The read-out of the TLDs was performed with a Harshaw reader model 5500. Further details on the TLD analysis and annealing procedures are described in [7]. The detectors were placed: along the phantom main axis inside cylindrical polyethylene holders (48 TLD pairs per holder, nine positions corresponding to the center of slices 3, 4, 5, 7, 9, 13, 17 and 21); in polyethylene tubes enabling depth-dose measurements in a 25 mm xy grid (inside slices 3 (72 TLD pairs), 4 (104 TLD pairs), 5 (68 TLD pairs), 14 (260 TLD pairs) and 20 (180 TLD pairs)); embedded in polyethylene belts for surface dose measurement (16 TLD pairs along the phantom main axis, 12 TLD pairs around slice 4 and 5 TLD pairs around slice 20).

The outputs of the diamond detector were collected with a UNIversal DOSimeter (UNIDOS) from PTW Freiburg. As the detector measures the charge produced from the passage of radiation, only relative values of the absorbed dose could be obtained. However, the high sensitivity of the diamond detector allowed an accurate characterization of the dose profile even very far away from the target volume (≈400 mm), where the dose dropped down to a few μGy·treatment-Gy^{-1}. The detector was placed either on the surface or inside the phantom along its main axis at slices 1, 3, 4, 5, 7, 9, 11, 14, 17, 21 and 26.

A picture of the phantom is shown in Fig. 1; the slices equipped with either TLD detectors or the diamond detector are specifically marked.

The irradiation

The list of facilities involved in the experiments is reported below together with details on the beam type and delivery system:

(a) 25 MV photons produced with an Elekta SL25 machine and delivered with IMRT technique at KGU (Frankfurt, Germany);

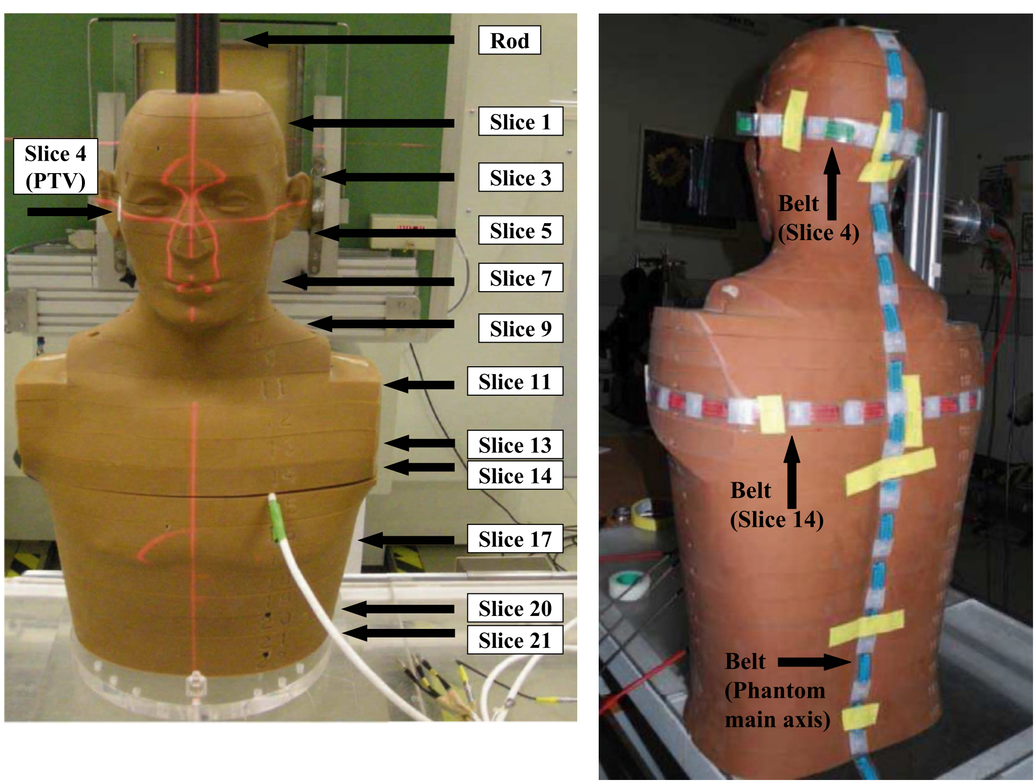

Fig. 1. The anthropomorphic RANDO phantom [6] used as target for all experiments. The slice containing the tumor volume (slice 4) is indicated. The position of all detectors placed inside the rod (TLDs: 3, 4, 5, 7, 9, 13, 17 and 21; diamond detector: 1, 3, 4, 5, 7, 9, 11, 14, 17, 21 and 26), the slices (TLDs: 3, 4, 5, 14 and 20) and on the surface (TLDs in the belts: 4, 14 and along the phantom main axis; diamond detector: 1, 3, 4, 5, 7, 9, 11, 14, 17, 21 and 26) are specifically marked.