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Original paper

Out-of-field doses from secondary radiation produced in proton therapy and the associated risk of radiation-induced cancer from a brain tumor treatment

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ABSTRACT

Purpose: To determine out-of-field doses produced in proton pencil beam scanning (PBS) therapy using Monte Carlo simulations and to estimate the associated risk of radiation-induced second cancer from a brain tumor treatment.

Methods: Simulations of out-of-field absorbed doses were performed with MCNP6 and benchmarked against measurements with tissue-equivalent proportional counters (TEPC) for three irradiation setups: two irradiations of a water phantom using proton energies of 78–147 MeV and 177–223 MeV, and one brain tumor irradiation of a whole-body phantom. Out-of-field absorbed and equivalent doses to organs in a whole-body phantom following a brain tumor treatment were subsequently simulated and used to estimate the risk of radiation-induced cancer. Additionally, the contribution of absorbed dose originating from radiation produced in the nozzle was calculated from simulations.

Results: Out-of-field absorbed doses to the TEPC ranged from 0.4 to 135 μGy/Gy. The average deviation between simulations and measurements of the water phantom irradiations was about 17%. The absorbed dose contribution from radiation produced in the nozzle ranged between 0 and 70% of the total dose; the contribution was however small in absolute terms. The absorbed and equivalent doses to the organs ranged between 0.2 and 60 μGy/Gy and 0.5–151 μSv/Gy. The estimated lifetime risk of radiation-induced second cancer was approximately 0.01%.

Conclusions: The agreement of out-of-field absorbed doses between measurements and simulations was good given the sources of uncertainties. Calculations of out-of-field organ doses following a brain tumor treatment indicated that proton PBS therapy of brain tumors is associated with a low risk of radiation-induced cancer.

1. Introduction

Radiotherapy delivered with protons can produce dose distributions with high target conformity and superior sparing of normal tissues in comparison to photon radiotherapy techniques [1–3]. As the number of proton facilities continuously increased in recent years, radiotherapy delivered with protons has become a viable treatment option for complex tumor types including pediatric brain neoplasms [4,5]. Proton therapy consequently plays an important role in modern clinical radiotherapy and is no longer limited to activities performed in research centers. This development has introduced new concerns and challenges for clinicians working in the field of radiotherapy. One of these is the assessment of patient dose originating from secondary radiation produced in proton nuclear interactions in the nozzle and within the patient [6–10]. This secondary radiation, especially the neutrons, can travel large distances giving rise to out-of-field doses to healthy organs located far from the primary treatment field. Concerns have therefore been raised regarding the associated risk of radiation-induced second cancers, which is expected to increase in the following years, as the long-term survival of radiotherapy patients improves and young patients receive radiotherapy more frequently [4,11]. Doses to organs located far from the primary treatment field are generally much lower than the doses to organs located close to the irradiated target volume where radiation-induced tumors are more likely to occur [12]. However, the incidence of radiation-induced tumors is evident also in tissues receiving lower doses [13,14]. To accurately evaluate the long-term outcomes associated with proton therapy, it is essential that the dose to healthy tissues from secondary radiation is assessed [6,15]. It has also been suggested that the risk of radiation-induced second cancers from specific treatment techniques, including the contribution

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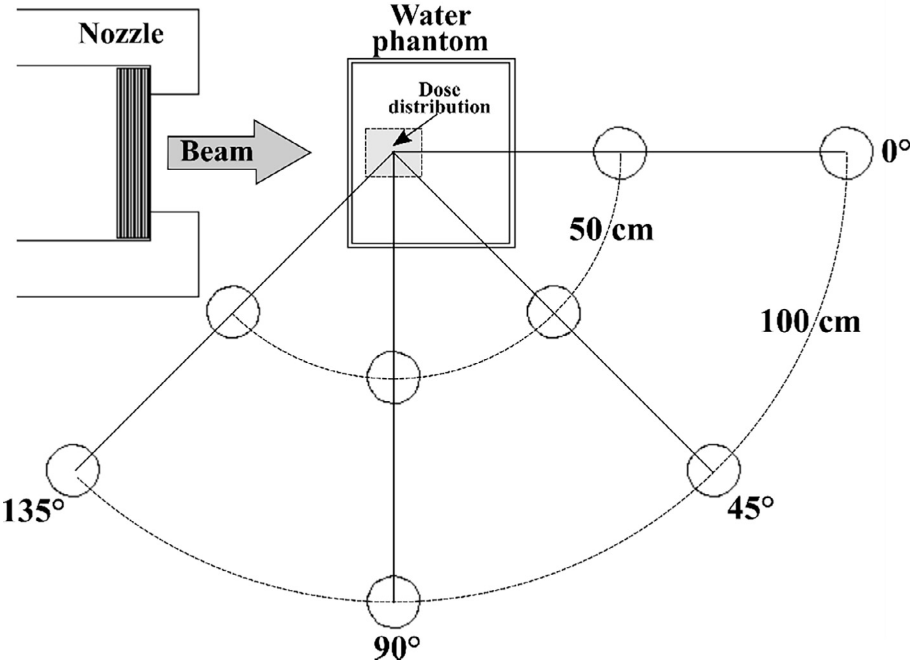

Fig. 1. Experimental setup of out-of-field measurements and MC simulations for cubic water phantom irradiation. The circles correspond to positions of the TEPC detectors.

from out-of-field doses, could be used as a complementary criterion in the clinical decision process [11,16].

Modern proton therapy facilities often have the capacity of delivering treatments using the pencil-beam scanning (PBS) technique. In comparison to the more traditionally employed proton passive scattering techniques, the production of secondary radiation associated with PBS is heavily reduced [6,10,17]. Secondary radiation from PBS treatments is mainly produced through nuclear inelastic interactions inside the patient [10,18] but the contribution coming from the nozzle should also be considered when evaluating out-of-field doses from irradiations with proton PBS techniques [19]. Out-of-field doses from secondary radiation are not routinely calculated for individual patients as most commercially available treatment planning systems (TPS) lack this capability [3,15]. Furthermore, the limited patient anatomy included on the computed tomography (CT) for treatment planning calculations does not offer the option of calculating the dose to remotely located organs.

The most common methods for determining out-of-field doses from secondary radiation are based on measurements or calculations using Monte Carlo (MC) simulations [7,20–23]. Measurements are usually performed with proportional counters, Bonner spheres, activation foils or track-etch detectors. The drawback of these techniques is that they do not allow for the assessment of out-of-field organ doses during the course of radiotherapy. Such doses are instead preferably determined from patient-specific calculations based on MC simulations which are considered the most accurate tool for such assessments [3,22,24,25]. The distribution of secondary radiation with regard to both energy and spatial distribution can vary greatly between different proton facilities and the MC model used for calculating out-of-field doses should consequently be validated against measurements with regard to both the primary beam characteristics and the out-of-field secondary radiation distribution [22].

In this study, MC simulations with the code MCNP6 [26] were benchmarked against measurements of absorbed doses from secondary radiation produced in a water phantom and a whole-body phantom irradiated with a clinically employed proton PBS system. Absorbed and equivalent out-of-field doses to several organs in a whole-body phantom were calculated for a clinical brain treatment plan and the associated risk of radiation-induced cancer was calculated. Also, the contribution of the out-of-field absorbed dose originating from nuclear interactions in the nozzle to the total out-of-field dose was determined through additional simulations.

2. Material and methods

The proton irradiations and measurements were carried out at the Skandion Clinic in Uppsala, Sweden, utilizing a dedicated PBS delivery system from IBA (Ion Beam Applications, Louvain-La-Neuve, Belgium). All measurements were carried out using two identical low pressurized TEPC detectors capable of detecting both photons and neutrons over a wide energy range; more details on the detector specifications and measurements can be found elsewhere [27–29]. The MC simulations were performed with the code MCNP6 [26], using a beam model previously validated with regard to primary proton beam characteristics [30]. The simulated proton beam started upstream in the nozzle and was transported in vacuum, passing through a monitoring ionization chamber and an exit window modelled from blueprints and material specifications provided by the vendor. Protons, neutrons and photons were transported and variance reduction was applied through geometry splitting and Russian roulette [31]. Each energy layer was simulated with 3–10 × 10^8 particle histories to achieve a relative standard deviation of less than 5%. The ENDF/B-VII.1 library [32] was used as primary proton cross-section library and the Bertini intranuclear cascade model [33] was used to model nuclear interactions.

2.1. Water phantom irradiation

Out-of-field absorbed doses to the TEPC detectors were determined from irradiating a 42 × 36 × 36 cm^3 WP1D water phantom (IBA dosimetry, Schwarzenbruck, Germany) with two different treatment plans, both producing a cubic 10 × 10 × 10 cm^3 dose distribution with a prescribed absorbed dose of 2.0 Gy to the center of each cube. The proton kinetic energies for the two treatment plans ranged in the intervals 78–147 MeV and 177–223 MeV, respectively, producing cubic dose distributions centered at depths of 10 cm and 26 cm, respectively. The incident proton beam was directed to the center of the phantom