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AMBIENT DOSE EQUIVALENT VERSUS EFFECTIVE DOSE FOR QUANTIFYING STRAY RADIATION EXPOSURES TO A PATIENT RECEIVING PROTON THERAPY FOR PROSTATE CANCER

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Abstract

The purpose of this study was to evaluate the suitability of the quantity ambient dose equivalent H*(10) as a conservative estimate of effective dose E for estimating stray radiation exposures to patients receiving passively scattered proton radiotherapy for cancer of the prostate. H*(10), which is determined from fluence free-in-air, is potentially useful because it is simpler to measure or calculate because it avoids the complexities associated with phantoms or patient anatomy. However, the suitability of H*(10) as a surrogate for E has not been demonstrated for exposures to high-energy neutrons emanating from radiation treatments with proton beams. The suitability was tested by calculating H*(10) and E for a proton treatment using a Monte Carlo model of a double-scattering treatment machine and a computerized anthropomorphic phantom. The calculated E for the simulated treatment was 5.5 mSv/Gy, while the calculated H*(10) at the isocenter was 10 mSv/Gy. A sensitivity analysis revealed that H*(10) conservatively estimated E for the interval of treatment parameters common in proton therapy for prostate cancer. However, sensitivity analysis of a broader interval of parameters suggested that H*(10) may underestimate E for treatments of other sites, particularly those that require large field sizes. Simulations revealed that while E was predominated by neutrons generated in the nozzle, neutrons produced in the patient contributed up to 40% to dose equivalent in near-field organs.

Keywords

proton therapy; stray radiation; radiation protection

I. INTRODUCTION

Approximately one in six men will develop prostate cancer during their lifetimes. Fortunately, there are many proven options available for the treatment of prostate disease, including radiation therapy. Contemporary intensity modulated X-ray therapy (IMXT) for localized prostate cancer provides 10-yr survival rates of ~65 to 70% (Ref. 1). Recent studies have suggested that escalating dose delivered to the clinical target volume (CTV) of prostate patients can significantly improve local tumor control.2 However, this increase in local control comes at the expense of higher doses to healthy tissues, which increases the probability of acute toxicity. A number of recent studies have indicated that external beam radiation therapy using high-energy proton beams can deliver highly conformal doses to the target volume while

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reducing the dose delivered to adjacent healthy tissues compared to current IMXT techniques.[3–5]

During IMXT of the prostate, healthy tissues adjacent to the target are exposed to radiation from the primary beam that has been scattered within the patient, while tissues farther from the field are exposed to leakage radiation from the accelerator head. As a result, long-term survivors of prostate radiotherapy face a small, but statistically significant, lifetime risk of developing a radiation-induced second cancer resulting from the dose delivered to healthy tissue outside the target volume.[6] One theoretical benefit from proton therapy is that a reduction in primary dose exposures to adjacent normal tissues can reduce the incidence of radiation-induced second cancers. However, available data suggest that risks from leakage radiation, particularly from high-energy neutrons, after proton therapy may be considerably higher than after IMXT (Ref. 7). The literature on second cancer risks following IMXT and proton therapy is sparse, disparate, and controversial; this may be a consequence of the different dosimetric quantities that have been reported.

In radiation protection, the quantity effective dose E is used to assess the risk to persons exposed to different forms of radiation. Calculation of E is based on tissue-weighting factors from the International Commission on Radiological Protection (ICRP) and equivalent dose (H_T) delivered to various organs and tissues. In some situations it is impractical to measure equivalent doses; in such cases the ICRP recommends the use of the operation quantity of ambient dose equivalent $H^*(10)$ to provide a conservative estimate of E. $H^*(10)$ is determined from a measurement or calculation of neutron fluence in air. The fluence combined with fluence–to–dose-equivalent coefficients provided by the ICRP are then used to calculate $H^*(10)$. Although these concepts are intended for use of radiological protection, they have also been adopted for use in medical irradiations. Numerous studies have utilized the in-air approach to characterize stray neutron doses from proton radiotherapy.[8,9] However, $H^*(10)$ was defined for persons exposed to uniform radiation fields incident on the whole body. For radiotherapy patients, who are exposed to highly nonuniform radiation fields, the suitability of $H^*(10)$ as a conservative estimate of E is unknown.

The aim of this study was to examine the suitability of $H^*(10)$ to conservatively estimate E from stray radiation in patients receiving passively scattered proton radiotherapy for prostate cancer. Using Monte Carlo methods, calculations of effective dose in an anthropomorphic phantom were compared to calculations of ambient dose equivalent based on fluence spectra in air.

II. METHODS AND MATERIALS

II.A. Typical Treatment Parameters

A prostate treatment for a typical patient was simulated using an MCNPX-based Monte Carlo model of a double-scattering proton therapy unit. The accuracy and suitability of the MCNPX code for proton therapy applications was previously established.[10–12] The treatment plan was designed to deliver the treatment using the passive-scattering beam line at the Proton Therapy Center–Houston and utilized a two-field, lateral, parallel-opposed field orientation.[13] Patient-specific machine settings (e.g., beam range, modulation, snout position, and range shifter setting) and hardware (e.g., aperture and range compensator) were extracted from the patient's treatment plan and imported into the Monte Carlo model (see Fig. 1). The required beam range for the selected patient was 24.7 cm in water, which necessitated a proton beam energy of 250 MeV from the synchrotron and ~4 cm of water-equivalent range shifter material, along with a required Bragg peak width of 9.0 cm.

II.B. Sensitivity to Changes in Field Parameters

We also varied several major treatment parameters to test the sensitivity of E and $H^*(10)$ to changes in those parameters. Holding other parameters from the typical treatment fixed, the proton energy incident upon the vacuum window was varied from 200 to 250 MeV. Similarly, the modulation width was varied from 1 to 13 cm, the field size was varied from 0 × 0 cm (closed aperture) to 15 × 15 cm, and the snout position (which determines the air gap, or distance between the range compensator and the patient surface) was varied from 48 cm (large air gap) to 30 cm (small air gap).

II.C. Calculation of Effective Dose

The effective dose from stray radiation E was determined for a typical prostate treatment using an anatomically realistic, stylized male phantom. We previously described the determination of effective dose in such a phantom for a typical proton treatment for prostate cancer. [14] The value of E was calculated as

$$E=\sum_T H_T \times w_T, \tag{1}$$

where tissue-weighting factors w_T were taken from ICRP Publication 60 (Ref. 15). Equivalent doses from stray radiation (neutrons and photons) in sensitive tissues H_T were calculated according to

$$H_T=\sum_R D_{T,R} \times w_R, \tag{2}$$

where

$D_{T,R}$ = absorbed dose from radiation R

w_R = radiation weighting factor.

Values of w_R were calculated using the spectral fluence incident upon each organ according to values provided in ICRP Publication 92 (Ref. 16). The sensitive tissues examined in this work were the lungs, stomach, liver, colon, esophagus, thyroid, bladder, rectum, breast, gonads, brain, and remainder. Values of E were reported per gray of therapeutic absorbed dose at the isocenter, i.e., the location of the center of the prostate gland.

II.D. Calculation of Ambient Dose Equivalent

Under the same treatment parameters, ambient dose equivalent from stray radiation $H^*(10)$ was calculated using methods described by Zheng et al.[9] Neutron spectral fluence $\Phi(E)$ was tallied in a 1-cm-radius air-filled sphere located at the isocenter. $H^*(10)$ was then calculated as the product of $\Phi(E)$, and the appropriate fluence–to–ambient-dose-equivalent conversion coefficient $h_\Phi(E)$ was calculated from ICRP Publication 74 (Ref. 17). Thus, the spectral ambient dose equivalent was calculated using

$$H^*(10)(E_i)=h_\Phi(E_i)\Phi(E_i), \tag{3}$$

where E_i is the mean neutron energy of the i' th neutron bin. Then, the total ambient dose equivalent was calculated as

$$H^*(10)=\sum_{i=1}^{n} H^*(10)(E_i)\Delta E_i, \quad (4)$$

where

n = total number of neutron energy bins

ΔE_i = neutron energy width of bin i.

III. RESULTS

H(10)* conservatively estimated *E* over the interval of treatment parameters common in proton therapy for prostate cancer. The calculated value of *E* for the typical treatment was 5.5 mSv/Gy, while the calculated *H*(10)* was 10 mSv/Gy. Figure 2 shows the sensitivity of the values of *E* and *H*(10)* to changes in treatment parameters. As the incident beam energy increased from 225 to 250 MeV, both *E* and *H*(10)* increased by ~30%. As the modulation width increased from 8 to 12 cm, both *E* and *H*(10)* increased by ~10%. As the snout position was changed from 30 cm (closest to the patient) to 48 cm (farthest from the patient), *E* decreased by 13%, while *H*(10)* decreased by 20%. As field size increased from 5 × 5 cm to 10 × 10 cm, *E* increased by 25%, while *H*(10)* decreased by 10%, though *H*(10)* was still conservative with respect to *E* for the 10- × 10-cm field size.

H(10)* did not conservatively estimate *E* for a larger interval of treatment parameters. As the incident beam energy increased from 200 to 250 MeV, both *E* and *H*(10)* increased by a factor of 2. As the modulation width increased from 1 to 13 cm, *E* increased by 75%, while *H*(10)* increased by 66%. As the snout position was changed from 30 cm (closest to the patient) to 48 cm (farthest from the patient), *E* decreased by 18%, while *H*(10)* decreased by 44%. As the field size increased from 0 × 0 cm to 15 × 15 cm, *E* increased by a factor of >2, while *H*(10)* decreased by 31%. *H*(10)* actually began to underestimate *E* when the field size exceeded 15 × 15 cm.

Outside the treatment field, H_T was predominated by secondary neutrons, which accounted for nearly 90% of all secondary H_T values. Secondary photons accounted for ~10% of total secondary H_T, independent of location within the patient. Equivalent dose H_T was highest in organs nearest the target volume (i.e., the prostate). Figure 3 shows H_T for selected organs. Virtually all neutrons observed far out of the therapeutic proton treatment field emanated from the treatment nozzle. As proximity to the CTV increased, the relative contribution to H_T from neutrons generated inside the patient increased, reaching a maximum of ~40% in the rectum. As the CTV (i.e., field size) increased, the contribution of internally created neutrons increased.

IV. DISCUSSION

For the typical prostate case studied in this work and for the interval of treatment parameters relevant for prostate treatment, *H*(10)* provided a conservative estimate of *E*. However, the sensitivity tests suggest that *H*(10)* may not be suitable for evaluating stray radiation exposure at other sites. Effective dose *E* was significantly influenced by changes in beam energy, modulation, field size, and snout position. *H*(10)* reflected the sensitivities of *E* to energy, modulation, and snout position but did not reflect the sensitivity of *E* to changes in field size. Because neutron production in the patient is not taken into account in calculations in air, *H*(10)* actually began to underestimate *E* when the field size exceeded 15 × 15 cm.

In conclusion, the presence of the patient can significantly influence the effective dose *E*. For prostate treatments, *H*(10)* provided a conservative estimate of *E*; however, these results may not apply for other sites, especially those where large field sizes are required. Therefore, when evaluating stray radiation exposure, one should consider production, scatter, and attenuation in the patient.

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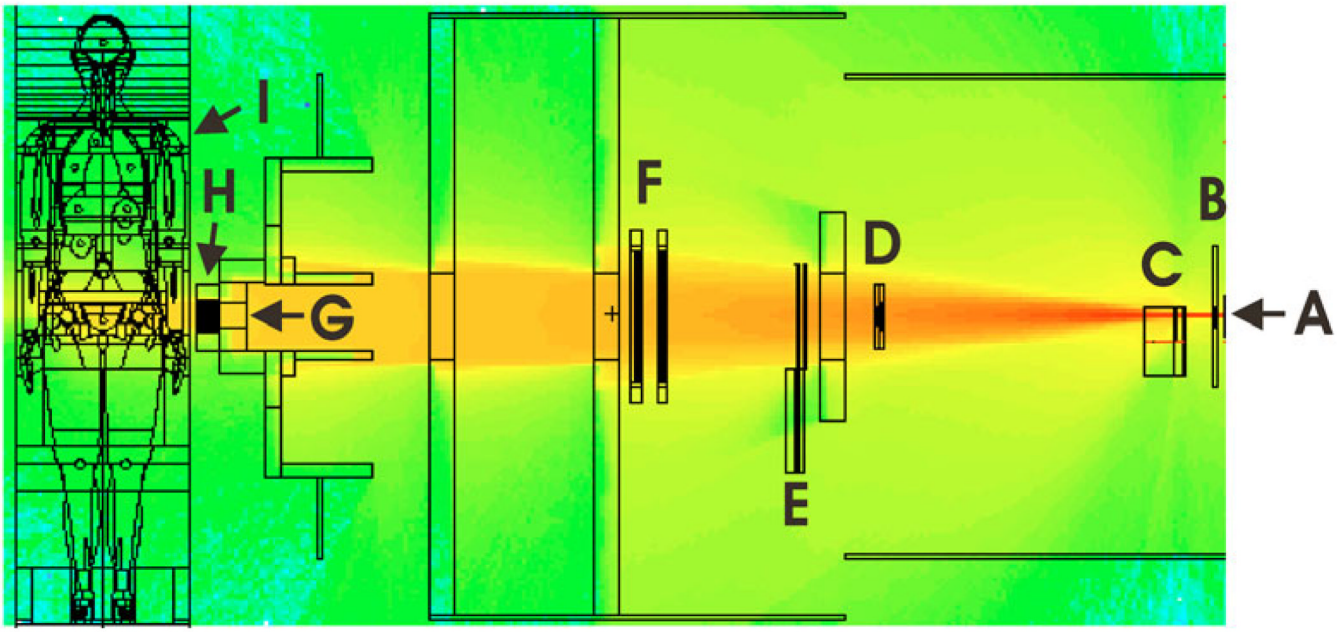

Fig. 1.

Simulated proton fluence (log scale) of prostate treatment using a Monte Carlo model of a double-scattering proton therapy treatment machine. A proton pencil beam (A) enters through a vacuum window and traverses a profile monitor (B). The rotating range modulator wheel (C) and second scatterer (D) spread the beam longitudinally and laterally. Also modeled are the range shifter plates (E), the main and subdose monitors (F) and the snout, which includes the patient-specific aperture (G) and range compensator (H). Absorbed dose from stray radiation was tallied in an anthropomorphic phantom (I).

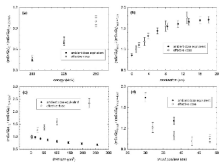

Fig. 2.
Equivalent dose from stray radiation as a function of the treatment parameters studied in this work. Specifically, effective dose in an anthropomorphic phantom and ambient dose equivalent in air were calculated for a prostate treatment as a function of (a) incident beam energy (normalized at 250 MeV), (b) modulation width (normalized at 1 cm), (c) field size (normalized at 0×0 cm^2), and (d) snout position (normalized at 48 cm).

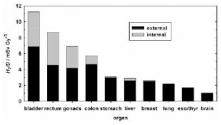

Fig. 3.

Equivalent dose from stray neutrons in selected organs for the simulated prostate treatment, including contributions from neutrons generated in the nozzle (external) and in the patient (internal).