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A surface energy spectral study on the bone heterogeneity and beam obliquity using the flattened and unflattened photon beams

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ABSTRACT

Aim: Using flattened and unflattened photon beams, this study investigated the spectral variations of surface photon energy and energy fluence in the bone heterogeneity and beam obliquity.

Background: Surface dose enhancement is a dosimetric concern when using unflattened photon beam in radiotherapy. It is because the unflattened photon beam contains more low-energy photons which are removed by the flattening filter of the flattened photon beam.

Materials and methods: We used a water and bone heterogeneity phantom to study the distributions of energy, energy fluence and mean energy of the 6 MV flattened and unflattened photon beams (field size = 10 cm × 10 cm) produced by a Varian TrueBEAM linear accelerator. These elements were calculated at the phantom surfaces using Monte Carlo simulations. The photon energy and energy fluence calculations were repeated with the beam angle turned from 0° to 15°, 30° and 45° in the water and bone phantom.

Results: Spectral results at the phantom surfaces showed that the unflattened photon beams contained more photons concentrated mainly in the low-energy range (0–2 MeV) than the flattened beams associated with a flattening filter. With a bone layer of 1 cm under the phantom surface and within the build-up region of the 6 MV photon beam, it is found that both the flattened and unflattened beams had slightly less photons in the energy range <0.4 MeV compared to the water phantom. This shows that the presence of the bone decreased the low-energy photon backscatters to the phantom surface. When both the flattened and unflattened photon beams were rotated from 0° to 45°, the number of photon and mean photon energy increased. This indicates that both photon beams became more hardened or penetrate when the beam angle increased. In the presence of bone, the mean energies of both photon beams increased. This is due to the absorption of low-energy photons by the bone, resulting in more beam hardening.

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Conclusions: This study explores the spectral relationships of surface photon energy and energy fluence with bone heterogeneity and beam obliquity for the flattened and unflattened photon beams. The photon spectral information is important in studies on the patient's surface dose enhancement using unflattened photon beams in radiotherapy.

1. Background

To make the delivery of some recent radiotherapy techniques such as intensity modulated radiotherapy and volumetric modulated arc therapy more efficient, medical linear accelerator capable of producing unflattened photon beams was developed.[1–5] With the removal of the flattening filter which generates a uniform beam profile for 3D-conformal radiotherapy, the output of the photon beam is highly increased.[6,7] For example, the Varian TrueBEAM linear accelerator can produce 1400 monitor units (MU) and 2400 MU per minute for the 6 and 10 MV photon beams, respectively. This dose rate from the flattening-filter free linear accelerator is about 2–3 times higher than the conventional accelerator producing flattened photon beams, and can shorten the treatment time.[8,9] Therefore, the patient throughput can be increased. Moreover, for the increasingly popular hypofractionated and stereotactic body radiotherapy, the unflattened photon beam is useful.[10–15] As some patients may be undergoing some kind of breath hold technique to manage respiratory motion issues, a fast treatment is necessary to take into account the patient's comfort and intrafraction organ motion.[12]

While it is advantageous to use an unflattened photon beam in radiation dose delivery, the exclusion of the flattening filter from the beam has some dosimetric concerns. The removal of the flattening filter largely decreases the beam attenuation and increases the photon fluence, but it also affects the photon energy distribution or beam quality.[16–18] The presence of the flattening filter uses to remove a large number of low-energy photons and results in beam hardening. For the unflattened photon beam, however, these low-energy photons are part of the beam and contribute to the dose deposition in the photon beam build-up region close to the patient surface. Compared to the flattened photon beam, though unflattened beam has less head scatter and leakage, measurements and Monte Carlo simulations have found that irradiation of the unflattened photon beam results in a higher surface dose than the flattened beam.[19,20] This indicates that the low-energy photons may play an important role in the surface dose enhancement of the unflattened beam. It is therefore worthwhile to compare the photon energy and energy fluence spectra between the flattened and unflattened beams. For unflattened beams, it is useful to identify in which low-energy range the photons have a higher intensity.

Apart from the presence of extra low-energy photons in the unflattened photon beams, it is well-known that the surface dose is also affected by heterogeneities close to the build-up region and the variation of beam obliquity.[21,22] Heterogeneities close to the patient surface such as bone, affects the backscatter contribution to the surface dose. This dosimetric impact is an issue in the lung and head-and-neck radiotherapy,[23] where the rib and skull are close to the patient surface and the bone backscatter would affect the photon beam energy spectrum. It is therefore worthwhile to investigate the different effects of the flattened and unflattened photon beams on the backscatter photons arising from the bone heterogeneity due to their different beam qualities. Furthermore, as the patient's external contour is curved and not perfectly perpendicular to the incident photon beam, beam obliquity is inevitable and would affect the surface dose in radiotherapy. It is found from measurements and Monte Carlo simulations that surface dose increases with an increase of beam angle.[21,24] However, spectral variations of photon energy and energy fluence in the beam obliquity for the flattened and unflattened beams have still not been reported.

2. Aim

In most previous dosimetric studies on unflattened photon beams, the flattening filter from a conventional linear accelerator was not designed in dose measurements or Monte Carlo simulations, respectively.[7,18,25–27] It should be noted that these conventional linear accelerators were not designed to produce clinical unflattened photon beams. In this study, the Varian TrueBEAM linear accelerator specifically designed to produce clinical unflattened photon beams was used. Photon energy and energy fluence spectra at surface were calculated by Monte Carlo simulations using the water and bone heterogeneous phantom (bone phantom). Through spectral comparisons of photon energy and energy fluence, variations of the unflattened beam quality in the presences of bone heterogeneity and beam obliquity were analyzed.

3. Materials and methods

3.1. *Water and bone heterogeneous phantom*

To compare the photon energy and energy fluence spectra with and without the bone heterogeneity, a water and bone phantom with the same dimension (13 cm × 20 cm × 20 cm) was used in our Monte Carlo simulations. The bone phantom in Fig. 1 has a bone layer with thickness equal to 2 cm. This bone layer was sandwiched by two water layers with thicknesses equal to 1 cm (on top of the bone layer) and 10 cm (under the bone layer). The bone layer was positioned within the build-up region of the 6 MV photon beam with the depth of maximum dose equal to 1.5 cm. In the Monte Carlo simulation, the ICRPBONE700ICRU bone in the EGSnrc-based Pegs4 dataset was used (ICRP 1975).[28] The density of the bone layer