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Dosimetric dependences of bone heterogeneity and beam angle on the unflattened and flattened photon beams: A Monte Carlo comparison

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HIGHLIGHTS

- Dosimetric impact of bone heterogeneity in the presence of unflattened and flattened photon beams was compared.
- Surface and depth dose of unflattened and flattened photon beams varying with the beam angle were compared.
- Depth dose deviation due to the presence of bone was sensitive to the beam obliquity.
- Surface dose deviation between the unflattened and flattened beams became smaller with an increase of beam angle.
- Surface dose and range of depth dose ratios (unflattened to flattened beam) decreased with an increase of beam angle.

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ABSTRACT

The variations of depth and surface dose on the bone heterogeneity and beam angle were compared between unflattened and flattened photon beams using Monte Carlo simulations. Phase-space files of the 6 MV photon beams with field size of $10 \times 10\ cm^2$ were generated with and without the flattening filter based on a Varian TrueBeam linac. Depth and surface doses were calculated in a bone and water phantoms using Monte Carlo simulations (the EGSnrc-based code). Dose calculations were repeated with angles of the unflattened and flattened beams turned from 0° to 15°, 30°, 45°, 60°, 75° and 90° in the bone and water phantoms. Monte Carlo results of depth doses showed that compared to the flattened beam the unflattened photon beam had a higher dose in the build-up region but lower dose beyond the depth of maximum dose. Dose ratios of the unflattened to flattened beams were calculated in the range of 1.6–2.6 with beam angle varying from 0° to 90° in water. Similar results were found in the bone phantom. In addition, higher surface doses of about 2.5 times were found with beam angles equal to 0° and 15° in the bone and water phantoms. However, surface dose deviation between the unflattened and flattened beams became smaller with increasing beam angle. Dose enhancements due to the bone backscatter were also found at the water–bone and bone–water interfaces for both the unflattened and flattened beams in the bone phantom. With Monte Carlo beams cross-calibrated to the monitor unit in simulations, variations of depth and surface dose on the bone heterogeneity and beam angle were investigated and compared using Monte Carlo simulations. For the unflattened and flattened photon beams, the surface dose and range of depth dose ratios (unflattened to flattened beam) decreased with increasing beam angle. The dosimetric comparison in this study is useful in understanding the characteristics of unflattened photon beam on the depth and surface dose with bone heterogeneity.

1. Introduction

The use of flattening filter free or unflattened photon beam has become popular in radiotherapy recently (Cashmore et al., 2011; Fu et al., 2004; O'Brien et al., 1991; Titt et al., 2006; Vassiliev et al., 2009). Traditionally, in external beam conformal radiotherapy, flattened photon beams are created by a flattening filter in the linac head to produce a homogeneous dose distribution at the tumor target. However, for newer radiation dose delivery techniques such as intensity modulated radiotherapy and volumetric modulated arc therapy, the segmental field fluence is spatially and temporally modulated by the dose rate and field shape generated by the multileaf collimator. Therefore, flattened photon beam

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seems to be unnecessary (Vassiliev et al., 2006a, 2006b; Nicolini et al., 2011). Moreover, for stereotactic radiotherapy, whether the photon beam is flattened or not does not give significant deviation in dose distribution, because the peak of the unflattened beam profile is significant merely in large field size (Mok et al., 2011; Georg et al., 2011).

When the flattening filter of photon beam is removed, the weight of low-energy photon fluence in the beam increases (Sixel and Faddegon, 1995; Titt et al., 2006; Mesbahi and Nejad, 2008). This makes the unflattened photon beam less preventive, resulting in a lower depth dose compared to the flattened beam in water. On the other hand, in the absence of flattening filter at the central beam axis, the head scatter and leakage are reduced (Cashmore, 2008; Kragl et al., 2009). This leads to a lower out-of-field or peripheral dose. However, the main advantage of using the unflattened beam is still the increase of dose rate by removing the flattening filter. It is reported that with the newly developed beam generation system, the Varian TrueBeam linac is able to deliver dose rates up to 2400 monitor unit per minute (Fu et al., 2004). This would definitely decrease the treatment time and increase the patient throughput in radiotherapy. On the other hand, such high dose per pulse of unflattened beams would affect the current radiobiological models on the evaluation of cancer cell survival (Lohse et al., 2011). As removing the flattening filter can increase the radiation output, and decrease the head scatter and leakage, cancer treatment deliveries using intensity modulated radiotherapy, volumetric modulated arc therapy and stereotactic radiotherapy technique with unflattened photon beams can be benefited by the improvement in dose delivery efficiency.

The increase in weight of low-energy photon and decrease in head scatter and leakage also affect the surface dose of patient. The increase in the number of low-energy photons, which should be removed by the flattening filter, from the unflattened beam contributes energy deposition in the build-up region of the patient, and therefore increases the surface dose compared to the flattened beam. However, decreases of head scatter and leakage due to the absence of flattening filter from the unflattened beam lower the surface dose. It is interesting to investigate which of the above factors is more significant, leading to an increase or decrease of surface dose for the unflattened photon beam (Wang et al., 2011). Apart from the presence of flattening filter which would affect the surface dose, beam obliquity and bone heterogeneity in the build-up region would also have impact on the surface dose (Chow and Grigorov, 2007; Chow and Owrangi, 2012). It is noted that the photon fluence in the depth of patient would be affected by the obliquity of central beam axis, which results in a higher surface dose (Chow et al., 2010). Furthermore, the presence of bone heterogeneity would produce bone dose enhancement towards the patient surface (Chow and Owrangi, 2011). To date, though there are studies on the surface dose in unflattened photon beams (Wang et al. 2011; Huang et al. 2012), there is no related study concerning surface dose variations on the bone heterogeneity and beam angle.

In this study, Monte Carlo simulation was used to predict the depth and surface dose from the unflattened and flattened photon beams. The Varian TrueBeam linac was modeled here because it can produce unflattened and flattened megavoltage photon beams by selecting the flattening filter absence or presence in the central beam axis. Although there were studies on Monte Carlo simulations based on unflattened photon beams, dose calculations were mostly based on a simulation model by removing the flattening filter from a typical linac, which did not have the feature of producing a real unflattened beam (Titt et al., 2006; Vassiliev et al., 2006a; Ponisch et al., 2006; Dalaryd et al., 2010; Parasai et al., 2007). In addition, the Monte Carlo beams were cross-calibrated to the machine monitor unit in simulations of the unflattened and flattened photon beams. This is important because the Monte Carlo results can inform us the deviation of radiation output between the two beams with the same source output. In measurement, this is difficult to determine because the output of unflattened photon beam would have been calibrated by the dosimetric protocol as if the flattened beam is in water (Hrbacek et al., 2011). The aim of this study is to compare variations of depth and surface doses on bone heterogeneity and beam angle, between unflattened and flattened photon beams. Monte Carlo simulation using the EGSnrc-based code was used (Kawrakow and Rogers, 2000).

2. Experimental

2.1. Phantom and calculation geometry

Fig. 1 shows the bone heterogeneity phantom and beam geometry in this study. In Fig. 1, unflattened and flattened photon beams of 6 MV with field size equal to $10\times10\ cm^2$, used throughout this study, irradiated a phantom with a bone layer of 2 cm thickness. The bone layer was positioned under a 1 cm thick water layer on top of the phantom. This made the bone heterogeneity in the build-up region of the photon beams with depth of maximum dose equal to 1.5 cm. The bone density was equal to $1.75\ g/cm^3$ and the ICRPBONE700ICRU bone was used containing elements H, C, N, O, Mg, P, S, Ca and Zn in ratios of 4.69, 1.2, 0.29, 2.79, 0.0091, 0.34, 0.098, 0.52 and 0.00015, respectively (ICRP, 1975). The isocenter was set at a depth of 10 cm and the source-to-surface distance was equal to 90 cm. Apart from the photon beam angle of 0° as shown in Fig. 1, the beam was turned to 15°, 30°, 45°, 60°, 75°

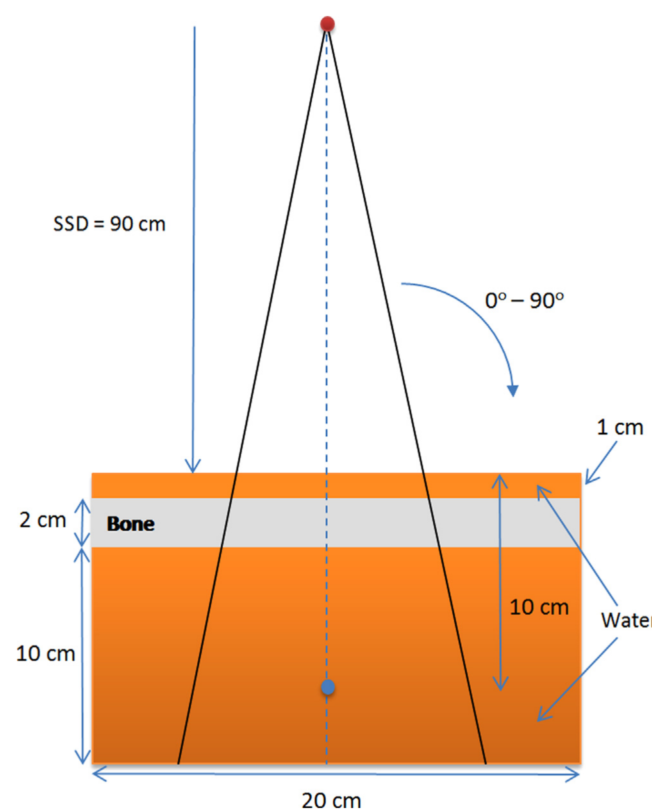

Fig. 1. Schematic diagram (not to scale) showing the calculation geometry of the bone phantom using the unflattened and flattened photon beams. The isocenter is at a depth of 10 cm from the phantom surface. The photon beams were rotated from 0° to 90° clockwise and the thickness of bone was equal to 2 cm. Dose calculations were repeated using the same beam geometry but a phantom with the bone replaced by water for dosimetric comparison.