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Monte Carlo evaluation of Acuros XB dose calculation Algorithm for intensity modulated radiation therapy of nasopharyngeal carcinoma

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ABSTRACT

Intensity-modulated radiation therapy is an effective treatment modality for the nasopharyngeal carcinoma. One important aspect of this cancer treatment is the need to have an accurate dose algorithm dealing with the complex air/bone/tissue interface in the head-neck region to achieve the cure without radiation-induced toxicities. The Acuros XB algorithm explicitly solves the linear Boltzmann transport equation in voxelized volumes to account for the tissue heterogeneities such as lungs, bone, air, and soft tissues in the treatment field receiving radiotherapy. With the single beam setup in phantoms, this algorithm has already been demonstrated to achieve the comparable accuracy with Monte Carlo simulations. In the present study, five nasopharyngeal carcinoma patients treated with the intensity-modulated radiation therapy were examined for their dose distributions calculated using the Acuros XB in the planning target volume and the organ-at-risk. Corresponding results of Monte Carlo simulations were computed from the electronic portal image data and the BEAMnrc/DOSXYZnrc code. Analysis of dose distributions in terms of the clinical indices indicated that the Acuros XB was in comparable accuracy with Monte Carlo simulations and better than the anisotropic analytical algorithm for dose calculations in real patients.

1. Introduction

Nasopharyngeal carcinoma (NPC) is a unique primary head and neck cancer arising from the nasopharynx with an estimated 86,700 new cases and 50,800 deaths in 2012 worldwide. High incidence rates are observed in southeastern China, Hong Kong, Malaysia, Indonesia and Singapore (Torre et al., 2015). Intensity-modulated radiation therapy (IMRT) with concurrent CDDP+5-FU chemotherapy is the primary treatment of choice for NPC because of its unique anatomical location and sensitivity to radiotherapy (Sun et al., 2014; Tao et al., 2015). IMRT provides the steep radiation dose gradient to produce a high degree of conformal tumor target coverage and a sparing of normal tissues. The accurate dose calculations are required to obtain therapeutic advantages of the IMRT.

One important aspect of IMRT for NPC patients is the need to have an accurate dose calculation algorithm to deal with the effects on the complex air/bone/tissue interface for achieving the cure without radiation-induced toxicities. Although Monte Carlo (MC) calculations had the best agreement with measured data within the inhomogeneous region (Ojala, 2014), these calculations require a large number of individual particles transporting in matter, thus resulting in an extensive computing time. This makes MC simulations virtually impractical in the clinical environment even with the variance reduction method, efficient sampling and coding technique (Bush et al., 2011). The anisotropic analytical algorithm (AAA), a convolution/superposition method, has been widely utilized for dose calculations in the treatment planning system (TPS). However, AAA was reported to lead to dose discrepancies in the air/bone/tissue region due to its inherent pencil beam kernel and independent depth/lateral scaling of the kernel for heterogeneity correction (Kan et al., 2013a).

The Acuros XB (AXB) algorithm provides a new advanced dose calculation method (Varian Medical Systems, Palo Alto, CA) applied in the TPS. It explicitly solves the linear Boltzmann transport equation by a deterministic method using discretized cross sections as radiations interact with the voxel volumes in matter. AXB makes use of the chemical composition of each material in the volume during radiation transport (Kan et al., 2013a, 2013b). Therefore, it directly accounts for the effects on tissue heterogeneities. With the single beam setup in

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phantoms, AXB has already been demonstrated to achieve the required accuracy compared with MC simulations but with faster computing speed and without statistical noise (Failla et al., 2010). For instance, Bush et al. (2011) compared AXB and MC calculated doses in a heterogeneous air/bone/lung phantom for 6 and 18 MV photon beams. They showed the maximum discrepancies were within 2% in lung, 1.8% in bone and 4.5% in air. Han et al. (2011) noted that the agreement between AXB and MC doses in a soft tissue/bone/lung phantom for 6 MV photon beam was within 2%.

Although the accuracy of AXB has been shown in heterogeneous phantoms, the clinical validation of AXB in real patients treated with IMRT should be established, especially for tumors in the head and neck region where a complex air/bone/soft tissue interface could cause dose perturbations. The present study aims to compare dose distributions calculated using the AXB algorithm and the MC simulation and to evaluate the clinical impact of AXB on NPC patients treated with the IMRT. Five NPC patients were studied with measurement-based MC (MBMC) calculations applying the electronic portal image data and the BEAMnrc/DOSXYZnrc code. Analysis of dose distributions in the planning target volume (PTV) and the organs-at-risk (OAR) were made. It indicated that the AXB algorithm was in comparable accuracy with the Monte Carlo simulation in the head and neck region.

2. Materials and methods

The AXB algorithm solves the linear Boltzmann transport equation of coupled photon and electron fluences in a voxel volume of matter through several steps. First, the external photon and electron sources are transported into the volume using ray-tracing techniques. Then, a finite-element method is used to find the energy- and angular-dependent fluences in this volume by applying discretized cross sections and stopping powers. Since the AXB utilizes mass densities and atomic compositions in the interaction cross sections, its calculation is analogous to the MC simulation. Comparing to the stochastic MC simulation, however, the AXB greatly reduces the computing time because of its deterministic computation. In the present study, the AXB version 13.026 in the Eclipse TPS (Varian Medical Systems, Palo Alto, CA) was used with a grid size of 2 mm^2. The AXB modeled four radiation sources: (1) primary source or bremsstrahlung photons created in the target, (2) extra focal source or photons resulting from interactions in the accelerator head (the flattening filter, primary collimators, and secondary jaws), (3) electron contamination, and (4) photons scattered from wedges (Failla et al., 2010). Five NPC patients treated with the IMRT received cumulative doses of 70 Gy in 35 fractions (Yeh et al., 2014). Seven coplanar 6 MV photon beams were used with the dynamic sliding window technique through a Millennium 120-leaf multi-leaf collimator (MLC) in the Varian 21EX linear accelerator.

MC simulations were performed using the MBMC method, which applied the electronic portal image data and the BEAMnrc/DOSXYZnrc code version 2007 (Rogers et al., 1995). The MBMC method has been described in detail previously (Lin et al., 2009) and is summarized here with the aid of Fig. 1. First, an incident parallel circular electron beam with a Gaussian intensity distribution of full-width at half-maximum equal to 0.12 cm and a mean electron energy of 6.3 MeV with 3% energy spread was incident onto the Varian 21EX linear accelerator tungsten target to generate an open-field phase-space file, i.e. data on energies, positions, directions, and weightings of every particles crossing the scoring plane at 80 cm from the source. Then, MC simulations were performed by applying the variance reduction technique with the directional bremsstrahlung splitting. The splitting-field source-to-surface distance was set at 100 cm. The splitting-field radius was equal to the field size. The Russian roulette plane was chosen above the bottom of the flattening filter. Here at least 3.0×10^7 particles were simulated in each IMRT field to reduce the uncertainty to ≤2% in the phase-space file. Next, an efficiency map of each IMRT field was obtained from data

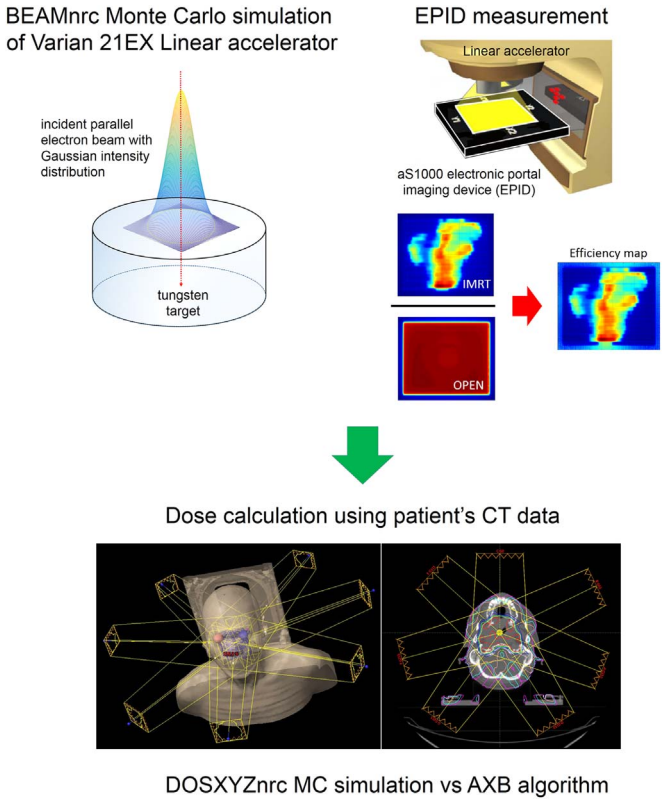

Fig. 1. The MBMC simulation setup.

collected on the amorphous silicon aS1000 electronic portal imaging device to adjust the weighting of each particle in the phase-space file. Further, the dose distribution in the patient was calculated using the DOSXYZ code (Rogers et al., 1995) and the efficiency map of IMRT photon beams transported through the patient. Finally, the calculated dose-to-medium could be converted to dose-to-water using the water-to-medium stopping power ratios (Siebers et al., 2000).

To allow uncertainties in the patient positioning, alignment and respiratory motion during the IMRT, PTV was determined to be the irradiated tumor volume plus a 3–5 mm margin. The PTV dose distribution was evaluated by $V_{>95\%}$, the percent PTV volume receiving ≥95% of the prescribed dose (70 Gy). The homogeneity index (HI) was evaluated by the ratio $(D_{2\%}\text{-}D_{98\%})/D_{50\%}$, where $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ are the minimum doses received by 2%, 50% and 98% of the PTV volume, respectively. A lower HI indicated a better dose homogeneity or less cold/hot spots (Kan et al., 2013a). Although air cavities were usually included in the PTV, a common practice among radiation oncologists during the treatment planning, PTV, $V_{>95\%}$ and HI were all determined by either including or excluding air cavities in the target volume in order to assess the dosimetric impact of air volume.

3. Results

All five NPC patients studied were successfully treated with the IMRT, i.e. disease-free with excellent local control after a median follow-up of 13 months. To compare their PTV dose distributions calculated using the AXB algorithm and the MC method, air cavities inside the PTV were either included or excluded. These air cavities produced higher statistical noise in the MC simulation due to fewer particle interactions in air than in soft tissues. As noted by De Smedt et al. (2007), the exclusion of air cavities in MC simulations resulted in more accurate dose distributions. Of all five patients, Table 1 lists their PTV including air, air inside the PTV, and PTV without air. On average, the air volume accounts for 10.8% of the PTV.

To evaluate the accuracy of the TPS algorithm in non-standard