Monte Carlo-based QA for IMRT of head and neck cancers

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\textbf{Abstract.} It is well-known that the presence of large air cavity in a dense medium (or patient) introduces significant electronic disequilibrium when irradiated with megavoltage X-ray field. This condition may worsen by the possible use of tiny beamlets in intensity-modulated radiation therapy (IMRT). Commercial treatment planning systems (TPSs), in particular those based on the pencil-beam method, do not provide accurate dose computation for the lungs and other cavity-laden body sites such as the head and neck. In this paper we present the use of Monte Carlo (MC) technique for dose re-calculation of IMRT of head and neck cancers. In our clinic, a turn-key software system is set up for MC calculation and comparison with TPS-calculated treatment plans as part of the quality assurance (QA) programme for IMRT delivery. A set of 10 off-the-self PCs is employed as the MC calculation engine with treatment plan parameters imported from the TPS via a graphical user interface (GUI) which also provides a platform for launching remote MC simulation and subsequent dose comparison with the TPS. The TPS-segmented intensity maps are used as input for the simulation hence skipping the time-consuming simulation of the multi-leaf collimator (MLC). The primary objective of this approach is to assess the accuracy of the TPS calculations in the presence of air cavities in the head and neck whereas the accuracy of leaf segmentation is verified by fluence measurement using a fluoroscopic camera-based imaging device. This measurement can also validate the correct transfer of intensity maps to the record and verify system. Comparisons between TPS and MC calculations of 6 MV IMRT for typical head and neck treatments review regional consistency in dose distribution except at and around the sinuses where our pencil-beam-based TPS sometimes over-predicts the dose by up to 10%, depending on the size of the cavities. In addition, dose re-buildup of up to 4% is observed at the posterior nasopharyngeal mucosa for some treatments with heavily-weighted anterior fields.

\section{Introduction}

IMRT has become more popular in the past few years \cite{1, 2}. The improved dose uniformity and conformality of IMRT are produced by field intensity modulation with a set of MLC of the linear accelerator (linac). However, dose computation in IMRT is more complicated than conventional treatment, because of the dosimetric effects introduced by the modulating MLC. Most commercial TPSs do not accurately model these effects and in addition, if the calculation model is pencil-beam-based the dosimetric accuracy in lungs and sinuses will be compromised \cite{3} owing to the limitations of the algorithm in dealing with the condition of lack of electronic equilibrium in these structures.
MC method [4] is an accurate and well-established technique for radiation transport calculations. In linac-based radiation therapy dose calculations using the MC technique, the initial step is the simulation of radiation interactions in the treatment head (including the MLC) and this is often carried out with the BEAM (or the newer BEAMnrc) code [5]. Based on the particle phase space data generated in the machine head, patient-specific simulation can then be performed. In this study, we used the MCSIM code system [6, 7] for dose calculation in patients with head and neck cancer and compared the MC results against a pencil-beam-based commercial TPS (CADPLAN™, Varian Medical Systems, Palo Alto, USA) in our clinic. We have also developed a simple PC-based GUI to simplify the MC simulation and dose comparison.

2. Implementation and benchmarking of MC code

In our present project with the MCSIM system, we used a photon beam model [8] for our Varian 2100C (Varian Medical Systems, Palo Alto, USA) linac. This method is based on iterative fitting of the measured beam data against the standard simulated phase space model previously obtained with the BEAM code for the linac of the same design. The advantages of using a beam model are the huge saving of storage space as compared with the ordinary set of phase space data and also the tremendous reduction in computing time in conducting full MC simulation of the machine head. For patient-specific dose calculations, MCSIM can perform IMRT dose computation using intensity maps reconstructed from the MLC leaf sequence file hence avoiding the time-consuming simulation for the MLC. In this work, we used directly the intensity map as segmented by the TPS (sliding-window mode) after checking the accuracy of the fluence map with measurement as demonstrated in Figure 1.

![Figure 1. Comparison between fluence measured with BIS and simulation using MCSIM (1% uncertainty at dose maximum) which has taken as input the segmented intensity map from CADPLAN. In the presence of limitations due to the leaf sequencer of the TPS and the lower resolution (2 mm) of MCSIM, the agreement is considered acceptable (about 1.0%) along the direction of leaf motion. The discrepancy along the longitudinal direction is larger (up to 4.5%) at the more prominent peaks and troughs of the profile.](image)

The validity of this intensity map-based approach was verified using the beam imaging system (BIS) from Wellhöfer (Schwarzenbruck, Germany). BIS is a large-area scintillator camera system suitable for fluence map measurement of megavoltage X-ray beams [9]. The scintillator (Gd₂O₂S) is backed with a 1 mm-thick copper plate for mechanical rigidity and electronic buildup. Background image subtraction is supported and linearity of the unit was checked with a series of exposures covering the dose range of interest. At a given energy and assuming that the copper plate provides a condition of electronic equilibrium, the measured energy fluence is proportional [10] to the dose absorbed in the phosphor. Improved accuracy can be obtained by deconvolution [11] of the image blurring due to optical “cross-talk”.

The accuracy of MCSIM in addressing heterogeneous geometries was also assessed with a purposely-built insert suspended in a large water phantom (Figure 2). This phantom insert consists of a pair of air cavity (fabricated with 1 mm-thick Perspex sheets) and Delrin™ (DuPont, Wilmington, USA) solid block each measuring 3 cm × 3 cm × 4 cm. Profile comparison in a 10 cm × 10 cm 6 MV field at a depth 0.5 cm below the blocks is depicted in Figure 3. Clearly, MC provides far better dosimetric accuracy in the presence of inhomogeneities, especially air cavity where CADPLAN under-predicts by about 2.5% at depth 0.5 cm below the cavity.

To build the MC simulation phantom, the patient’s CT images were reformatted to 128 × 128 using ctcreate [12] from the BEAM system. For a typical head and neck case, the voxel size of the simulation phantom is about 2 mm × 2 mm × 3 mm (resolution of dose matrix of TPS is 2.5 mm in all directions). We segmented the compositions of the patient to materials as air, soft tissue and bone. Standard MCSIM simulation parameters were employed and photon forcing was used as a variance reduction technique. Dose to water was reported for comparison with TPS which also reports dose to water. We used 10 off-the-shelf PCs to shorten the calculation times and this small cluster is managed by an in-house computer program called MCEval (under Microsoft Windows 2000) which is a MC control and dose evaluation program for comparing dose calculations between commercial TPSs and MC. The simulation time for a typical head and neck case is about 30 minutes in order to achieve a 2% uncertainty at the dose maximum. This uncertainty was estimated by re-running the total number of history using only one PC.

3. Graphical front-end for MC simulation and dose comparison
All MC calculation PCs (Linux-based) were NFS-connected to a file server for retrieval of MC database and storage of MC results. A master PC (also running Linux) was set up to run the NQS batch job system distributing the parallel MC tasks to the small Linux cluster. This master PC was controlled by MCEval remotely across the network using the rshell protocol. MCEval can disseminate remote Linux commands to facilitate all MC simulations and subsequent dose comparisons with a consistent user interface and data format.
Figure 4. Screenshot of main menu of MCeval containing tabs on (1) Patient Directory, (2) Image/Dose Curves, (3) DVH Plots, (4) Plan Setting and (5) MCSIM. The “DVH Plots” tab shown here is catered for DVH comparison between MCSIM and CADPLAN. Also shown on the “Image/Dose Curves” tab, the user can browse through the whole dose matrix displayable on top of the CT slices which can be overlaid with contoured internal structures of the patient.

Figure 4 is a screenshot of MCeval showing DVH and dose comparisons. This simple GUI consists of a pair of dose distribution comparison windows with panels on, (1) patient directory, (2) image and dose map browser, (3) DVH comparison window, (4) plan settings display and (5) MCSIM commands window. We now give a brief description of MCeval in routine dosimetric QA of IMRT for a head and neck case. The treatment planner saves an extra copy of the completed plan to a specific location in the CADPLAN file storage system. Through the network, MCeval retrieves this patient plan via NFS. All relevant plan details (including CT, dose matrix, DVH and fluence map) are displayed accordingly. A visual check is carried out to compare the TPS-segmented fluence maps and the BIS-measured intensity patterns. A copy of the fluence map is sent to the file server for storage and is later retrieved by MCSIM. The user can then move to the MC commands window for conducting the MC simulation. MCeval sends a remote Linux command (via rshell) to the master PC in the network to run ctcreate with an input file stipulating the network path of the patient’s CT images and settings of all other phantom parameters. During the execution of ctcreate, all the Linux echoes from the master PC are piped to a small window in MCeval for any diagnostic messages. The MC phantom is then stored in the file server for subsequent perusal by MCSIM. With user-selectable simulation parameters, MCeval writes 10 MCSIM input files (one for each PC and each with a different set of random number seeds) with copies sent to the file server. Using the standard EGS4 batch run command syntax, MCeval set up (again via rshell) all 10 MC jobs at the master PC which then distributes them to the Linux cluster using the NQS batch job queuing system. All EGS4 batch run echoes are also piped to a
MCeval window. When all MC jobs are finished, the dose values in each individual .3DDOSE dose file from MCSIM are added and the combined dose matrix is passed to MCeval for slice-by-slice comparison with CADPLAN. MCeval also calculates the MC DVHs based on the corresponding contoured structures in CADPLAN.

4. Dose comparison between MCSIM and CADPLAN in the head and neck

For clinical cases, we have performed MC dose re-calculations for over 50 head and neck patients, mainly carcinoma of the nasopharynx (NP). We will present 2 typical cases here and they all calculated to an uncertainty of 2% at the dose maximum and the MC dose curves are plotted with weighted-average of neighbouring dose points on each slice. The set of percent isodose lines of the MC simulation was obtained by normalising to the prescribed dose as given in the TPS. Our current acceptability criteria for the TPS-plan are based on visual assessment by an experience planner. The main objective is to identify any gross mismatches between the MC-plan and the TPS-plan. If a significant difference is found in the comparison, film measurement will be carried out using a standard IMRT phantom for further analysis.

Figure 5. Carcinoma of the left antrum treated with 6 MV X-ray IMRT. CADPLAN predicts full coverage where MCSIM accurately demonstrates the dosimetric effect of lack of scatter of the air in the cavity rendering a depression of dose by up to 10 % at and around it.

Figure 6. IMRT boost treatment for a nasopharyngeal cancer using 6 MV X-ray. The predominating anterior fields lead to a slight secondary re-buildup of dose distal to the NP lowering the mucosal dose by approximately 4 %.

Figure 5 depicts a plan comparison for a carcinoma of the antrum which was treated with a 7-field IMRT technique using 6 MV X-ray. Because of the larger size of this antral cavity, dose perturbation becomes more prominent as demonstrated by the MC calculation. CADPLAN predicts that the 90 % isodose line encompasses the whole target volume without considering adequately the lack of scatter of the missing tissues in the cavity. Dose re-buildup is seen in Figure 6 which shows a treatment plan for NP boost with beams coming mainly from the anterior direction. The dose at the NP mucosa is reduced at a consequence of this re-buildup.

5. Discussion and conclusions

Dosimetric accuracy at and around the sinuses in the head and neck should be assessed with extra caution. Our MC re-calculations can provide a means to double-check the dose calculation from the TPS. In our present work, full simulation of the MLC was not carried out and instead fluence map (as verified by measurement) segmented by the TPS leaf sequencer was taken as input for simulation in order to save computation time. In fact, full MLC-based simulation will definitely improve the accuracy of dose calculation but our goal at the moment is to compare the plans in a qualitative...
fashion leaving the verification of leaf segmentation to measurement. Future comparison will adopt
the gamma analysis approach which can illustrate the dose mismatch in a more quantitative way.

Measurement-based QA of IMRT consumes an ever increasing amount of resources. However,
fluence map measurement cannot be eliminated because of the need to verify the correct transfer of the
leaf sequences. Coupled with this fluence validation, our simple but efficient MC dose re-calculation
approach has helped to provide an alternative consistent and resource-saving QA scheme for IMRT of
the head and neck in the clinic.

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