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IMRT treatment Monitor Unit verification using absolute calibrated BEAMnrc and Geant4 Monte Carlo simulations

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Abstract.

Intensity Modulated Radiation Therapy (IMRT) treatments are some of the most complex being delivered by modern megavoltage radiotherapy accelerators. Therefore verification of the dose, or the presecribed Monitor Units (MU), predicted by the planning system is a key element to ensuring that patients should receive an accurate radiation dose plan during IMRT. One inherently accurate method is by comparison with absolute calibrated Monte Carlo simulations of the IMRT delivery by the linac head and corresponding delivery of the plan to a patient based phantom. In this work this approach has been taken using BEAMnrc for simulation of the treatment head, and both DOSXYZnrc and Geant4 for the phantom dose calculation. The two Monte Carlo codes agreed to within 1% of each other, and these matched very well to our planning system for IMRT plans to the brain, nasopharynx, and head and neck.

1. Introduction

IMRT is performed commonly in modern radiotherapy centres around the world on a daily basis. It involves delivering many multileaf collimator (MLC) modulated beams to build up a complex 3D sculpted dose distribution to a patient's tumor while sparing as much healthy tissue as possible. It is therefore comprised of many regions of high dose gradient change, and so quality assurance of IMRT plans is a detailed and constantly evolving practice. The first step in this quality assurance chain is the prediction of the dose by the planning system. One such common method to perform this task is with Monte Carlo simulations, where the same plan is delivered to a CT-based Monte Carlo patient phantom and the doses compared. This however is not an absolute dose method as there is no fundamental connection made between the number of histories in the simulations and dose delivered to a phantom.

In this work we have performed absolute calibrated Monte Carlo simulations, where we simulate the linac head and calibrate our model to replicate exactly what the linac delivers when it is told to deliver 1 MU. The first step taken is to calibrate the linac head simulation by determining the number of electrons required to produce 1 MU (1 cGy) for the reference setup of a 10x10 cm^2 field, as well as to record the amount of charge collected in the linac head monitor chamber. Once known, all future simulations get corrected by a factor which is directly


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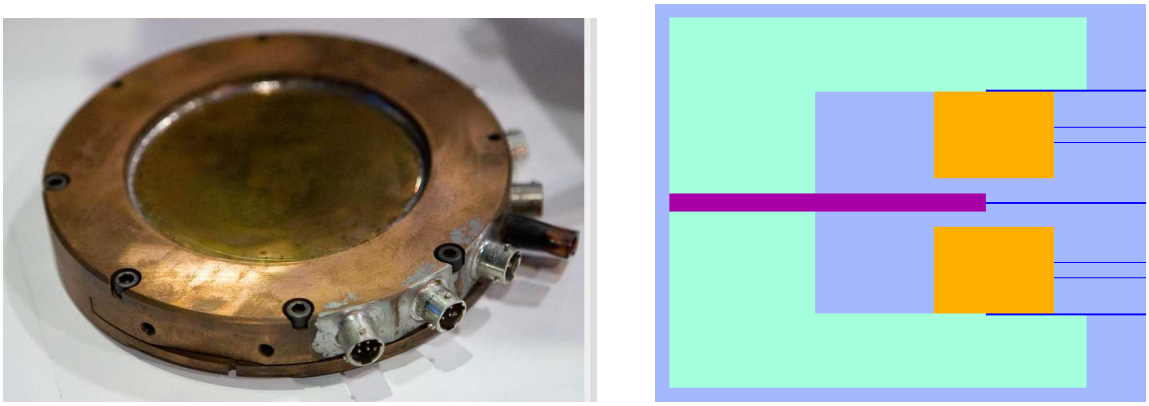


Figure 1. Left: Image of the Varian monitor chamber. Right: Implementation of the monitor chamber in BEAMnrc using two CHAMBER component modules.

the ratio of monitor chamber dose to that of the reference field. This replicates what the linac is delivering, i.e. it knows what charge collected in the monitor chamber is producing 1 cGy.

2. Methods

2.1. BEAMnrc Monte Carlo simulations

The linac head (Varian 2100C) was modeled using the EGSnrc user code BEAMnrc[2]. This simulation was used to generate IAEA format phase space files below the MLC's (558 mm from the target), as well as to model the dose scored (including the backscatter) in the treatment head monitor or ion chamber. All the typical component modules were used to model the 2100C linac head; x-ray target (SLABS), primary collimator (CONS3R), exit window (SLABS), flattening filter (FLATFILT), ion chamber (CHAMBER, CHAMBER), mirror (MIRROR), Y and X-jaws (JAWS, JAWS), Millenium 120 leaf MLC (DYNVMLC), and the reticle (SLABS). Particular attention however was paid to the monitor chamber to get the best possible match to the real chamber geometry. This was achieved by coupling two CHAMBER modules back-to-back. This allowed a very close match by including all the sensitive layers and surrounding frame material, see figure 1. For all BEAMnrc simulations the global ECUT= 0.521 MeV, and global PCUT= 0.01 MeV. The low ECUT value is important for tracking secondary electrons in the monitor chamber accurately[3].

2.2. Absolute Calibration Simulations: DOSXYZnrc and Geant4

At our centre 1 MU (6MV beam) corresponds to 1 cGy at D_{max} where SSD = 100 cm. In practice the measurement is done at 10 cm depth and related back to D_{max} by: $D_{10} = 0.661 \times D_{max}$ as per the PDD characteristics of our centres' 6MV beam. This setup was replicated in both Geant4 (version 9.6.p01)[4] and DOSXYZnrc[3] (version V4-r2-4-0) and both codes used the same phase space file generated by the BEAMnrc simulation as input. Simulation were run to determine how many electrons would produce 1 cGy at D_{max}.

2.3. Patient Phantom Simlations: DOSXYZnrc and Geant4

CT based phantoms were setup in both DOSXYZnrc and Geant4. These simulations read the corresponding IAEA phase space files from the BEAMnrc treatment head simulations. Similar to the BEAMnrc simulations, no variance reduction techniques where used in either code. For the DOSXYZnrc simulations the global ECUT = 0.7 MeV, while the global PCUT= 0.01 MeV. The remaining transport settings followed the default approach outline in the DOSXYZnrc

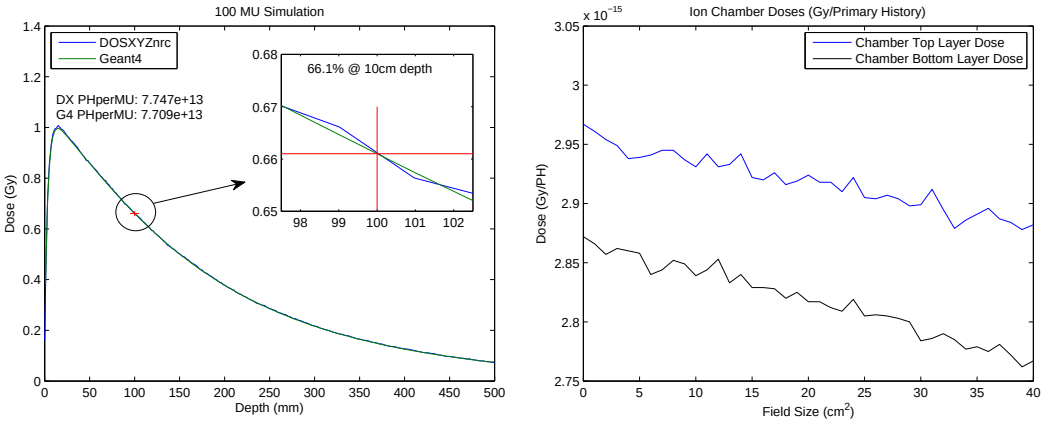


Figure 2. Left: Absolute calibration simulation results. An excellent match is seen between Geant4 and DOSXYZnrc. Right: Monitor chamber doses for symmetric beams from 0x0 cm^2 to 40x40 cm^2.

manual. For Geant4, the Livermore Low-Energy physics models were uses with 1 mm range cuts throughout the phantom and surrounding.

In terms of implementing a Patient CT based phantom "ctcreate" was used for the DOSXYZnrc simulations while for Geant4 in-house code was used to replicate the ctcreate approach. In both codes only air and water were employed to somewhat match what Pinnacle performs. The conversion from CT number to water density was done in 0.05 g/cc bins ranging from 0.3 to 5.5 g/cc. Below 0.3 g/cc the material was set to air. In both codes the voxel resolution was set to 2 CT pixel x 1 CT slice resolution, or 1.95x1.95x2 mm in x, z, y directions accordingly.

3. Results

3.1. Benchmark Linac Model, Absolute Calibration, and Chamber Dose

Linac commissiong data was used to benchmark our Monte Carlo model. This included ion chamber and diode measurements for 5x5, 10x10, 20x20, 30x30 and 40x40 cm^2 field sizes at depths of 15 mm, 50 mm, 100 mm, 200 mm, and 300 mm. A 2%/2 mm gamma match between the Monte Carlo simulations and measured data was achieved for the entire range of field sizes and depths for the following settings of the electron beam striking the x-ray target: Spot size = 0.9x1.2 mm, FWHM = 1%, Peak = 6.00 MeV.

The absolute calibration simulation results (see fig 2) concluded that the number of electrons required to produce 1 MU at our reference conditions was: $7.709 \times 10^{+13} \pm 1\%$ (Geant4) and $7.747 \times 10^{+13} \pm 1\%$ (DOSXYZnrc). The 0.5% match is within simulation error and so these values could be considered identical.

Figure 2 also shows the monitor chamber doses for symmetric beams from 0x0 cm^2 to 40x40 cm^2. Dose was scored in both sensitive layers and the average taken. It is clear from this plot that there is around 3% change from 0x0 cm^2 to 40x40 cm^2, enforcing the need to correct for the backscatter to the monitor chamber inside the Monte Carlo simulation.

To the best of our knowledge the only comparison (for a 6MV Varian 2100C beam) we can draw with from the literature is from the 2005 work by Popescu et al [1]: $8.124 \times 10^{+13} \pm 1.0\%$. In this setup the SSD was 98.5 cm rather than 100 cm as in our case. There has also been a change to the 6MV flattening filter since 2006 and so we estimate the differences to be a combination of both different setup and different geometry. Regardless of this value, it is the monitor chamber dose ratio to the reference field that is the most important for this work.

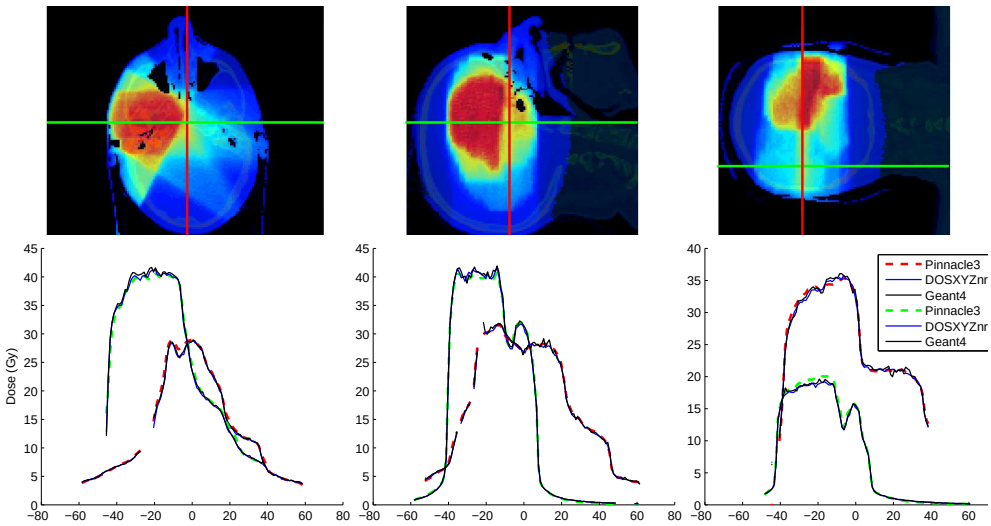


Figure 3. IMRT plan comparison for a 4 field (54 segment) brain IMRT plan.

3.2. IMRT Plan comparisons: Brain, Nasopharyx, and Head and Neck

Figures 3-5 show comparisons between Pinnacle and DOSXYZnrc/Geant4 for a brain, nasopharynx, and a head and neck cancer IMRT case. Both the brain and nasopharynx plans are 4 fields with 56 segments in total while the head and neck is 9 fields with 129 segments. The monitor chamber backscatter correction factors for each plan were brain: 1.005, 0.996, 0.999, 1.007, nasopharynx: 0.994, 1.003, 0.999, 0.997, and head and neck: 1.005, 1.009, 1.000, 1.009, 1.009, 1.001, 1.006, 1.000, 0.999. At most there is only about a 1% correction as these beams all were of similar shape to to the reference field of 10x10 cm^2. In reality the largest corrections take place for either the largest open fields, or blocked fields where a Y-jaw (closest to monitor chamber) is mostly closed to allow off-axis treatments.

In each of figures 3-5 the top row shows the Pinnacle dose overlayed on the CT slice and two corresponding profiles of interest through each orientation. The bottom plots show the dose profiles as described by the lines drawn in the top plots. In all plots the dose to air has been removed to improve clarity. In the 4 field brain and nasopharynx cases there is excellent agreement between the two Monte Carlo codes (within error estimates of $< \pm 2\%$) across the profiles shown. These match Pinnacle very well also, with only a minor deviation in the brain case for one profile far from the tumor site (right bottom plot). For the more advanced 9-field head and neck case there is again excellent agreement between the Monte Carlo codes. We can see a slight overprediction of the dose by Pinnacle as compared to Monte Carlo across some sections of the green (horizontal) profile shown on the right. As can be seen this lies along a sharp dose gradient and so we would naturally attribute this to endleaf transmission effects not being modeled as accurately as the Monte Carlo approach.

4. Conclusions

Absolute calibrated Monte Carlo simulations have been successfully set up and tested for comparing our planning system predictions on the MU's for IMRT treatment plans. Excellent agreement is seen between Geant4 and DOSXYZnrc for dose calculation in water only phantoms, and generally excellent agreement between Monte Carlo and Pinnacle where expected. Future work will include benchmarking the MLC Monte Carlo model against experimental transmission measurements.

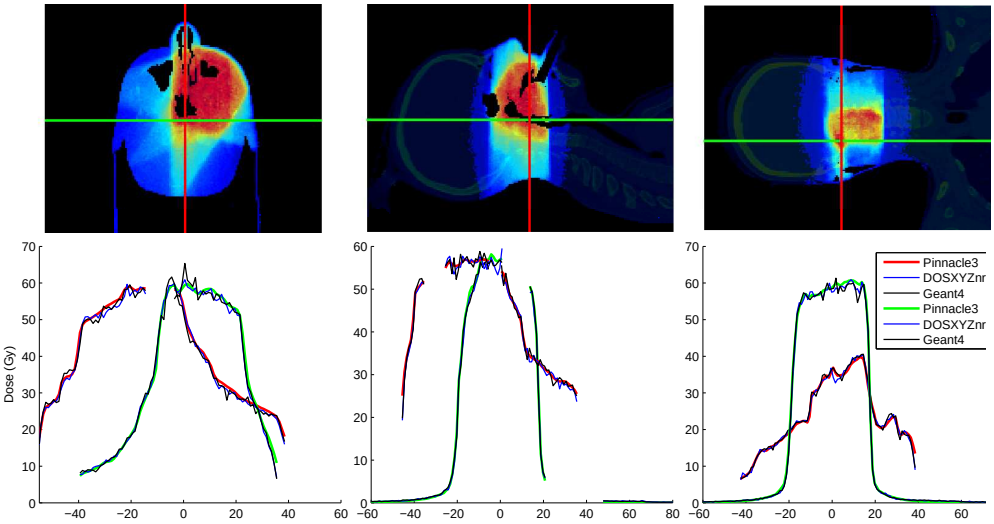


Figure 4. IMRT plan comparison for a 4 field (54 segment) nasopharynx IMRT plan.

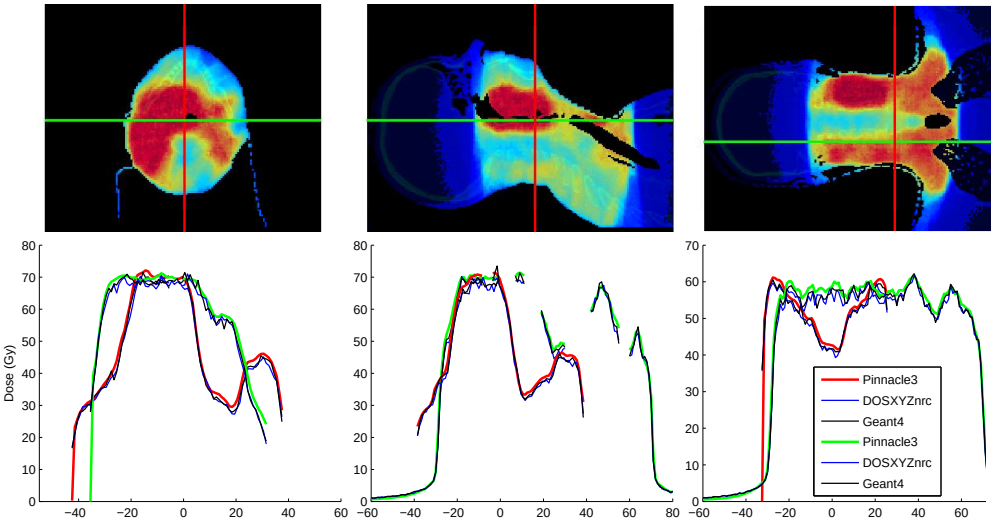


Figure 5. IMRT plan comparison for a 9 field (129 segment) head and neck IMRT plan.

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