A Monte Carlo tool for combined photon and proton treatment planning verification

J Seco¹, H Jiang², D Herrup¹, H Kooy¹ and H Paganetti¹

¹ Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA
² University of Arkansas for Medical Sciences, 4301 W. Markham Street, Little Rock, Arkansas 72202 USA
email: jseco@partners.org

Abstract. Photons and protons are usually used independently to treat cancer. However, at MGH patients can be treated with both photons and protons since both modalities are available on site. A combined therapy can be advantageous in cancer therapy due to the skin sparing ability of photons and the sharp Bragg peak fall-off for protons beyond the tumor. In the present work, we demonstrate how to implement a combined 3D MC toolkit for photon and proton (ph-pr) therapy, which can be used for verification of the treatment plan. The commissioning of a MC system for combined ph-pr involves initially the development of a MC model of both the photon and proton treatment heads. The MC dose tool was evaluated on a head and neck patient treated with both combined photon and proton beams. The combined ph-pr dose agreed with measurements in solid water phantom to within 3%/3mm. Comparison with commercial planning system pencil beam prediction agrees within 3% (except for air cavities and bone regions).

1. Introduction
Since Monte Carlo simulations take into account the physics of particle interactions on a particle-by-particle basis they are considered to be the most accurate method to simulate doses in radiation therapy. They consider tissue inhomogeneities by using exact material properties, e.g. elemental composition, electron density, mass density or ionization potential and also the exact position of inhomogeneities along the beam path and its scattering effects are modeled accurately. It has been shown in the literature that the difference between dose distributions obtained with pencil-beam algorithms and Monte Carlo generated dose distributions can be significant for certain treatment areas and beam configurations (1).

The motivation of building a MC tool for a combined photon and proton at MGH is two-fold: (i) for large treatment fields significant skin sparing is achieved if photon fields are used instead of proton fields, even though the sharp fall-off of the proton dose deposition in the Bragg peak region leads to a significant reduction in the dose deposited beyond the tumor site and (ii) from a logistical point of view the proton therapy unit is overloaded with patients that will need to wait
several months before treatment. Therefore, substituting some proton beams for photon beams will significantly reduce the patient waiting time.

Monte Carlo dose calculation is currently not commercially available for photons and protons combined. This paper describes the clinical implementation of a combined photon+proton Monte Carlo dose calculation. Some of the details are specific to treatment techniques used at Massachusetts General Hospital (MGH) and the Monte Carlo code used at MGH. However, the tasks required for clinical Monte Carlo and the strategy of approaching them is mostly facility and code independent.

2. Material and methods
Several Monte Carlo (MC) codes such as DPM (2), MCNP (3), BEAM/EGS (4,5), Geant4 (6), PENELOPE (7), and others are being used in radiation therapy. Monte Carlo methods have been applied to verify the results of the approximate dose calculation algorithms implemented in commercial treatment planning tools.

II.1. Photon Monte Carlo dose calculation
For phase space calculation in the VARIAN 2100C/D photon linear accelerator we use EGSnrc and for patient dose calculation we use DPM. The electron and photon cutoff energies were respectively 700 keV and 50 keV. MC commissioning involved matching calculated and experimental results for both percentage depth dose (PDD) and off-axis ratios (OAR) obtained from standard open fields 4x4, 6x6, 8x8, 10x10, 13x13, 15x15, 17x17, 20x20, 25x25, 30x30, 35x35 and 40x40 cm² measured in water tank 50x50x40cm³, adopting the method described by Seco et al (8). Once the MC reproduces the measured data, a calibration factor is required to convert MC units of dose per unit incident particle into dose per monitor unit. A correction is used to take into account backscatter from the X and Y jaws into the monitor chamber using the method proposed by Jiang et al (9).

Figure 1. (a) Depth dose for 4x4, 10x10 and 30x30 cm² fields, (b) dose profiles at depths of 5, 10 and 20cm for 40x40cm² field and (c) output factor evaluation for Monte Carlo.

II.2. Proton Monte Carlo dose calculation
For proton dose calculations the Geant4 MC code was used because it has been successfully tested and benchmarked for proton therapy (10). Electromagnetic interactions as well as nuclear interactions (11) have to be considered. The latter contribute significantly to the dose distribution (12-14). Geant4 calculates material dependent ionization potentials internally but it also allows the user to define new settings. We achieved a better agreement of our simulations with experimental results when setting the ionization potentials based on the ICRU (15). All relevant particles are included in the simulation: protons, neutrons, helium ions, deuterons, tritons, photons, and electrons. The production threshold for photons is set to ensure that particles are ‘created’ only if the projected CSDA-range is bigger than 1 mm in air. Several pristine depth dose distribution were measured and compared with simulations. The proton beam characterized by the incident proton energy, energy spread, beam spot size and beam angular distribution. The energy spread was found to be most critical because it influenced the width of the Bragg peak, the slope of the distal fall-off and the peak-to-plateau ratio (10). The treatment head simulation was benchmarked against measurements in phantoms (water, lung equivalent and bone equivalent material) showing excellent agreement. As an example, measured dose distributions of a spread-out Bragg peak (SOBP) can be reproduced to within 1mm in range (R) and 2mm in modulation (M) (see figure 2).

![Figure 2.](image)

Figure 2. (a) Pencil beam Bragg curves for various energies (b) and for various SOBP.

Absolute dosimetry of proton therapy fields is performed using the method published in Paganetti (16).

II.3. Simulating patient geometry and material composition

In photon therapy, electron density is used to characterize the energy loss in any medium. For protons, instead of electron density, stopping power is used to accurately characterize energy loss of protons in a media. The two different methods are incorporated in the Hounsfield unit conversion via a lookup table for HU to electron density (for photon calculations) and into relative stopping power (for proton calculations). The conversion of the CT number into tissue parameters for the MC dose algorithms was performed using Schneider et al (17). In this method, HU for 71 human tissues, whose characteristics were taken from literature, were calculated. Mass density and elemental weights of any HU were obtained via linear interpolation. The HU from –1000 to 1600 were binned into 24 groups: one group for air (-1000 to -950), one group for lung tissue (-949 to -120), seven groups for soft tissues (-119 to +120), and fifteen groups for skeletal tissues (+121 to +1600). Additional points were added in the bone region as described by Vanderstraeten et al (18).
The dose-to-medium to dose-to-water conversion can be performed for the photon beam using Siebers et al (19) method. In the case of protons, MC only provides dose-to-medium, no conversion dose-to-water is performed.

II.4. Combined photon and proton patient dose

A nasopharynx patient was used as a test patient, where this patient was treated at MGH with 8 IMRT photon fields and 13 proton fields. A comparison between solid water measurements and MC predictions was performed for all fields. In addition, a comparison between MC and the planning system pencil calculation was performed of both photon and proton beams individually and for the combined plan.

The advantage of having a combined MC tool for dose calculations is that it allows the dosimetric and clinical verification of the combined plan in a unique format. This plan can then be read either by the commercial planning system XiO (Computerized Medical Systems Inc., St. Louis MO) or using an in-house developed analysis package: dose comparison application (DCA). With the unique format it is now possible to normalize the combined treatment plan; in addition the dose-volume histogram (DVH) and gamma-index evaluation of the clinical plan can also be performed. In the present study, the photon MC is performed using DPM due to its accuracy and speed at performing photon dose calculation. The photon dose calculations can also be performed using Geant4, however this was not done due to the substantial inefficiency in photon dose calculations.

3. Results

III.1 Photon and proton MC validation in solid water

In figure 3, an example set of IMRT photon fields are compared to measured values in solid water phantom. The spatial resolution of the Monte Carlo dose cubes is 2 mm while for the water phantom its 5mm. Agreement between measurement and Monte Carlo was within 3%/3mm using gamma index comparison. Similar studies were performed for the proton beams and agreement was within 2%/2mm in the penumbra region, while a 2%/1mm agreement was obtained in the Bragg peak fall-off region.

![Figure 3. Monte Carlo and measurement of photon IMRT dose in solid water phantom.](image-url)
III.2 Photon and proton MC for patient dose calculation

In figure 4 we compare the MC photon dose calculation obtained for 2 IMRT beams with pencil beam (CMS) dose calculations. The dose algorithms have good agreement except in the regions of bone structure and air cavities (right side of the patient). Differences between MC and pencil beam are mainly due to weaknesses in pencil beam accurately modelling dose deposition in air cavities and bones. The MC verification of the plan shows that a slightly higher dose will be deposited in and around the base of the skull relative to the prediction given by the commercial dose algorithm (c.f. figure 4). For the proton beam passive scattering (or range modulation) method was used to treat the patient.

![Figure 4. Monte Carlo and pencil beam proton and photon IMRT dose in nasopharynx patient.](image)

4. Discussion and conclusion

A tool for patient- and field-specific photon and proton Monte Carlo calculation of dose has been introduced at MGH using the DPM for photons and GEANT4 for protons. Patient specific CT processing is performed using the CT-calibration table composed 14 material, which allows for assignment of elemental tissue composition based upon literature data and mass-density allocation within each specific material.

The combined system involved the development of a combined MC tool and format for dose calculation and evaluation of clinical plans at MGH. This combined proton and photon format, can now be used for several things such as plan normalization, dose verification and even biological evaluation of the tumor control probability and normal tissue complication probability.

The MC results are generally found in very good agreement with measured data obtained in solid water phantoms. In the case of patient dose calculations, the new MC system can now be used for verification purposes of the commercial planning systems available at MGH, which are CORVUS and XiO for photons and XiO for protons. The developed MC approach was tailored to the needs of the clinical dose calculation at MGH. Nevertheless, it can be easily adapted to use for other facilities, provided that the phase space beam information is known.

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