The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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MONTE CARLO DOSE CALCULATIONS BY EXTRACTION OF MACHINE BASED INCIDENT FLUENCE MAPSFROM A 3D PLANNING SYSTEM

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ABSTRACT

Monte Carlo (MC) - based treatment planning systems are hindered by the computation time spent to achieve acceptable accuracy. Much of the importance of MC planning lies in accounting accurately for individual differences in tissue geometry and composition. A great part of the computation time could be spared if one could avoid transporting particles through the head of linear accelerator (phase space approach) or utilize the beam data from the treatment planning system (fluence map technique).

In this work we have developed an approach for MC calculation (parallel version of the PENELOPE MC code) of dose distributions created with 6 MV photon beams (Varian 2100CD accelerator) by utilizing initial information about the beam from a commercial treatment planning system (TPS). In such an approach TPS represents initial beam conditions for the superposition algorithm resulting in accurate dose distribution for homogeneous medium. Concomitantly, PENELOPE accounts for realistic particle transport inside the homogeneous and inhomogeneous phantoms.

The results of the commissioning of this mixed algorithm are presented in this paper. These results of dose distribution inside homogeneous and inhomogeneous phantoms are compared with the doses obtained from TPS calculations with superposition algorithm and measurements with film.

Key Words: Monte Carlo, convolution/superposition, phase space

1 INTRODUCTION

The success of radiation therapy chiefly depends on the accuracy of dose administered to the patient. The precision with which the dose is delivered relies on the algorithms describing the physics of the ionizing radiation within the patient and the methods of dose delivery. There have been continuous efforts to create more accurate treatment planning systems to provide an improved quality of dose administration [1-6].

The specific hypothesis of this work is that the extraction of the phase space of the particles from a treatment planning system and the calculation of the dose to the patient with an accurate Monte Carlo (MC) algorithm improves dose accuracy and can reduce calculation time. The hypothesis is supported by the following findings.

First, since the engineering of a phase space is time consuming and requires commissioning of the whole algorithm, the possibility of using precalculated and commissioned phase space would accelerate dose calculation process.

Second, information about the collimated beam is present in the treatment planning phase space and it does not require additional modeling and calculating of particle transport in the collimating system. The examples of collimation components in the linear accelerator are the jaws, multi leaf collimators (MLC), and compensators.

Third, MC algorithms used for calculation of the dose in the presence of heterogeneities are more accurate than the semi-empirical kernel superposition algorithms of the treatment planning systems [1]. Moreover, the improvement in dose calculation is the largest when high spatial resolution, materials with heterogeneities, and small treatment fields are considered.

Based on these findings, the focal point of this work is on incorporating both phase space approach and MC algorithms. The methods and materials are intended to facilitate an inclusive evaluation of the dose accuracy and the reduction of calculation time achieved with the proposed technique.

1.1 Methods and Materials

1.1.1 Dose calculation with treatment planning system and dose measurements

Convolution/superposition algorithm [7] employed in a commercial treatment planning system (TPS) is considered as one of the most accurate among semi-empirical dose calculation algorithms [1]. For photon beams with field sizes within the clinical range the convolution/superposition algorithm provides the dose distributions matching the measured doses in a homogeneous phantom and, in special cases, in a inhomogeneous phantom [1, 4, 6].

We obtained dose distribution calculated with superposition algorithm in three dimensions both for homogeneous solid water phantom (30cm x 30cm x 30cm) (X,Y,Z) and a phantom with a 3 cm thick air (PENELOPE) or vacuum (TPS and PENELOPE) slab placed at depth of 5 cm (Fig.1) for a 6 MeV photon field of 5cm x 5cm field size shaped with collimator jaws. Source–to–axis distance (SAD) was 100 cm and source-to-skin distance (SSD) was set to 85 cm. Calculation volume for superposition algorithm was 10cm x 10cm x 20cm and dose was calculated in each point of interest (here at transversal (XY) and sagittal (ZY) planes) with calculation grid of 0.1 cm. Value of total energy released per unit mass was set to 4.0. The data from a commissioned Varian 2100CD [8] linear accelerator was utilized to create a virtual accelerator for dose calculation in the TPS.

For the same setup as for the dose calculation in the TPS a set of measurements was performed on the commissioned Varian 2100CD linear accelerator with EDR2 film (Eastman Kodak, Rochester, NY).

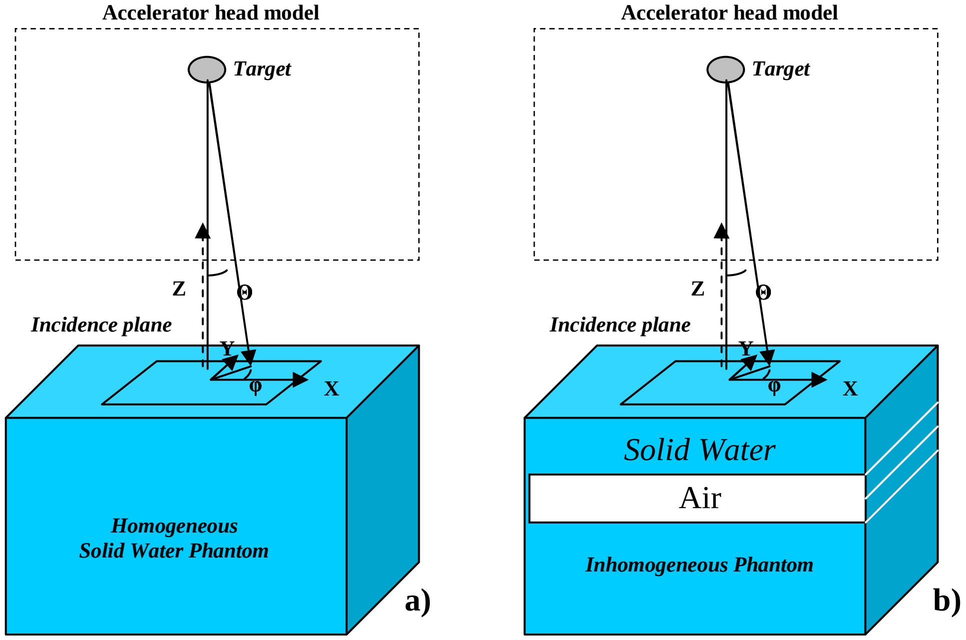

Figure 1. SAD setup for solid water phantom s: (a) homogeneous and (b) inhomogeneous

1.1.2 Dose calculation with PENELOPE

We extracted the phase space for the same 6 MeV photon field in the form of fluence map, which provides an energy spectrum for each point of the field. The phase space was then used for the sampling of particles for MC simulation. The sampling was achieved with acceptance-rejection method [9, 10] from the fluence map for the beam with the same field size and SAD defined for TPS dose calculation.

The sampling resulted in obtaining probability for each primary photon to start with certain energy from a given point on a surface plane (Z=15 cm) (Fig.1), which is perpendicular to the beam's central axis. The direction for each particle was assumed to be along the ray coming toward the particle's starting point from a point source located at (0,0,100). Due to discrete nature of incident fluence map and, consequently, of the rays it was necessary to provide a realistic dose distribution. This was done with bilinear interpolation in order to increase number of starting points of the particles on the surface plane within the boundaries of the fluence map (Xmin = -6.47 cm, Xmax = 6.47 cm) and (Ymin = -6.47 cm, Ymax = 6.47 cm). PENELOPE's [11] energy cutoffs were set equal to 200 keV. Angular deflection and maximum average fractional energy loss between consecutive hard elastic events were both are set to 0.09. To insure reliability of mixed simulation algorithm Maximum allowed step length between consecutive hard elastic events was chosen to be 0.5 cm. Calculations were done with simulation of 2.1×10^{9} histories to reduce statistical uncertainty to less than 3% for 0.1cm x 0.1cm x 0.1cm voxels. The simulation of the desired number of histories was achieved by running calculations for a total of 8 hours on 40 processors with 375MHz clock cycle on a IBM RS/6000 SP system [12].Transversal and sagittal planes were chosen to demonstrate dose distribution. Fluence map had 0.1 cm resolution in X and Y direction. Energy spectrum of photons passing each pixel of the radiation field consisted of 24 bins. A value from incidence fluence corresponded to each point in (E,X,Y) space, where E is the energy of a particle and X and Y are coordinates of points in the plane of the radiation field.

1.2 Results

Systematic approach includes consideration of various field sizes and energies of photon beam as well as location, size, and shape of air cavity. Results presented here are only for an intensity modulated (IMRT) "pyramid" field (Fig. 2) of 6 MeV photon beam for homogeneous and inhomogeneous set-ups of solid water phantom.

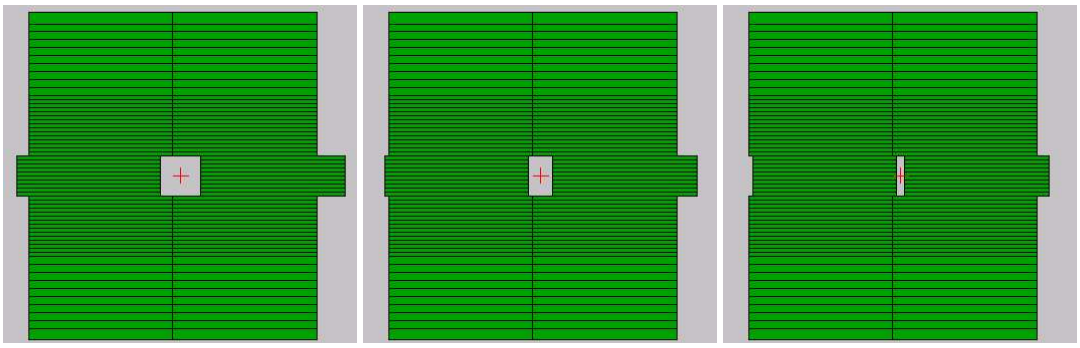

Figure 2. Intensity modulated radiation therapy (IMRT) field creating a "pyramid" intensity profile with 3 stationary fields with sizes (left to right) 5 cm x 5 cm, 3 cm x 5 cm, and 1 cm x 5 cm, respectively (field outlines prepared with MLC Shaper created by Varian Inc. , Palo Alto, CA).

The percentage depth dose figure for the homogeneous phantom (Fig.1a) was normalized to the depth of 10 cm in the region far from the range of the contaminant electrons scattered from the machine head and not accounted in the input for the MC simulation. The results are shown in Figure 3.

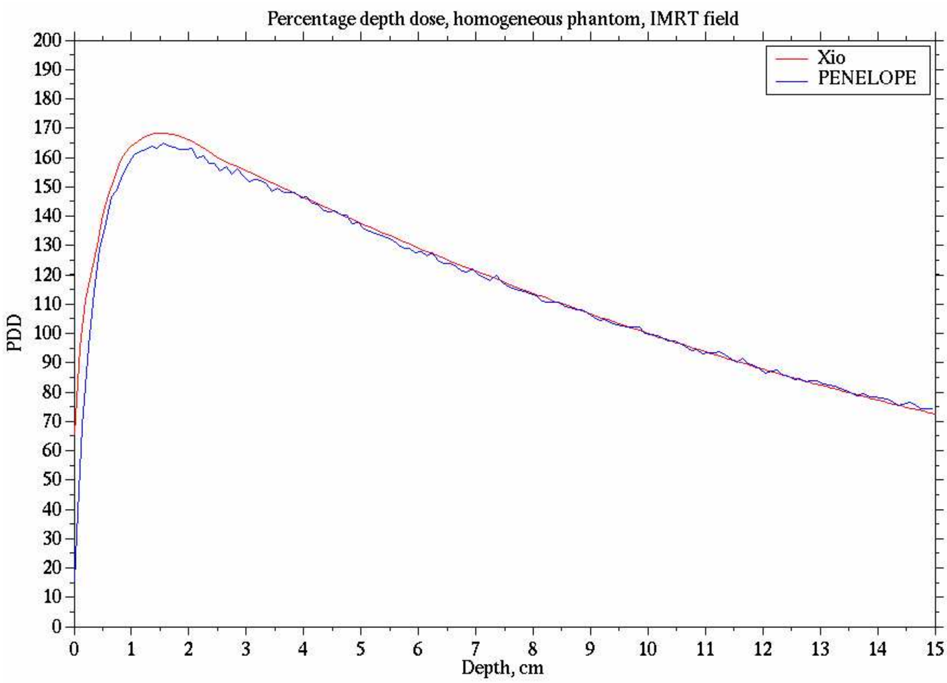

Figure 3. Percentage depth dose (PDD) along the central axis for MC code PENELOPE (blue) and TPS superposition algorithm (red). The results are normalized to the depth of 10 cm.

The data shows a good agreement between PENELOPE and TPS for most of the depths except the superficial region of the phantom. The dose profiles also reveal a close match of data produced with PENELOPE and TPS methods (Fig 4).

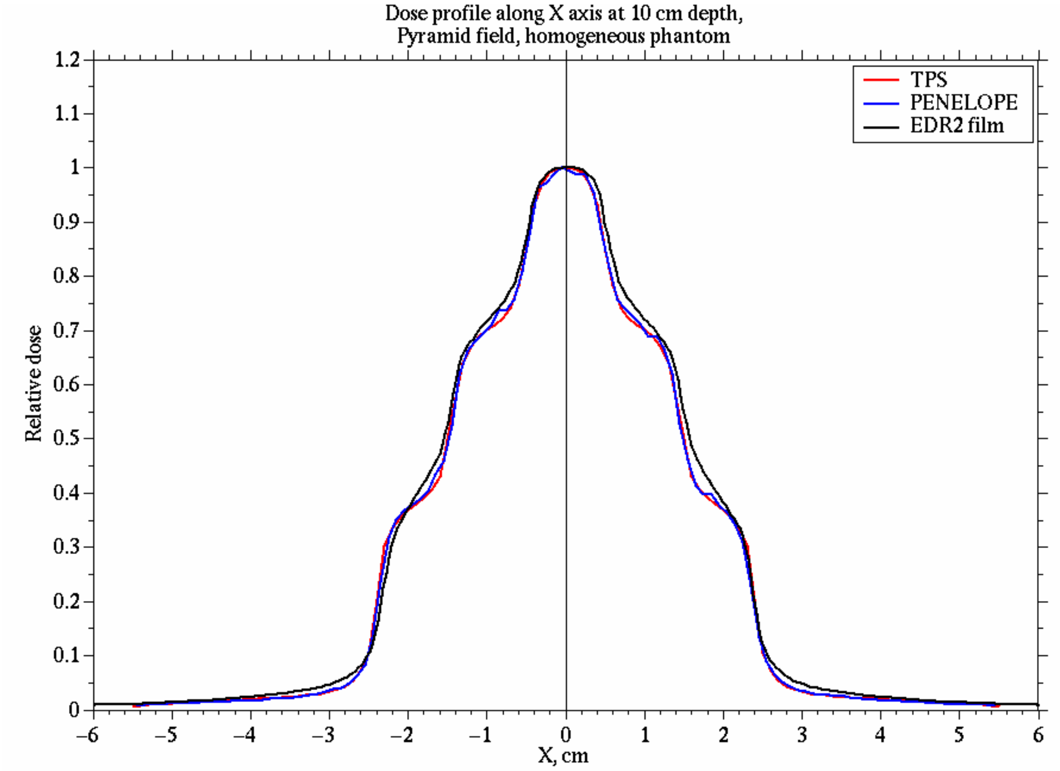

Figure 4. Dose profile relative to the dose at 10 cm along the axis calculated with MC code TPS superposition algorithm (red), PENELOPE (blue), and measured with film EDR2 (blue).

The comparison of the calculated dose and the dose measured with an extended dose range silver halide film EDR2 for IMRT "pyramid" film(Fig. 4) shows that TPS data was closer to the PENELOPE dose rather than to the measured one. One could expect such close match between PENELOPE and TPS in a homogeneous media at the depths greater than the range of contaminant electrons. In particular similar dose values appeared because the inputs for both methods were identical and particle transport with superposition algorithm in a homogeneous media can produce the dose as accurate as the dose calculated with accurate MC codes.

The mismatch between the film measurements and calculated values is believed to be mainly due to the approximation of particle's initial direction to be along the fan-like rays. The discrepancy could also come from extrapolating of the fluence maps of the commissioned fields with certain sizes to obtain fluence map for a field of any size. In addition, the discrepancy between the measurement and calculation could also be due to inability of silver halide film to precisely measure the dose, especially from the particle with low energies [13].

The dose distributions for an inhomogeneous phantom (Fig. 1b) are shown on Figure 5. The shape of the dose distribution in the build-up region shows small change for the slab composed either of air or vacuum. The dose profile revealed that TPS and PENELOPE dose calculations differ within 1 cm of the build-up region along the beam axis with a discrepancy of up to 20 % between MC and TPS dose values (Fig.5a,b).

In the plane perpendicular to the beam axis and located in the build-up region at a depth of 10 cm the measured dose was slightly higher than the calculated doses. With respect to the measured dose the peripheral underdosage in the distribution calculated with TPS and MC (Fig.5b and 5c) was a result of the TPS algorithm shortcomings and relatively small correction of it by MC.

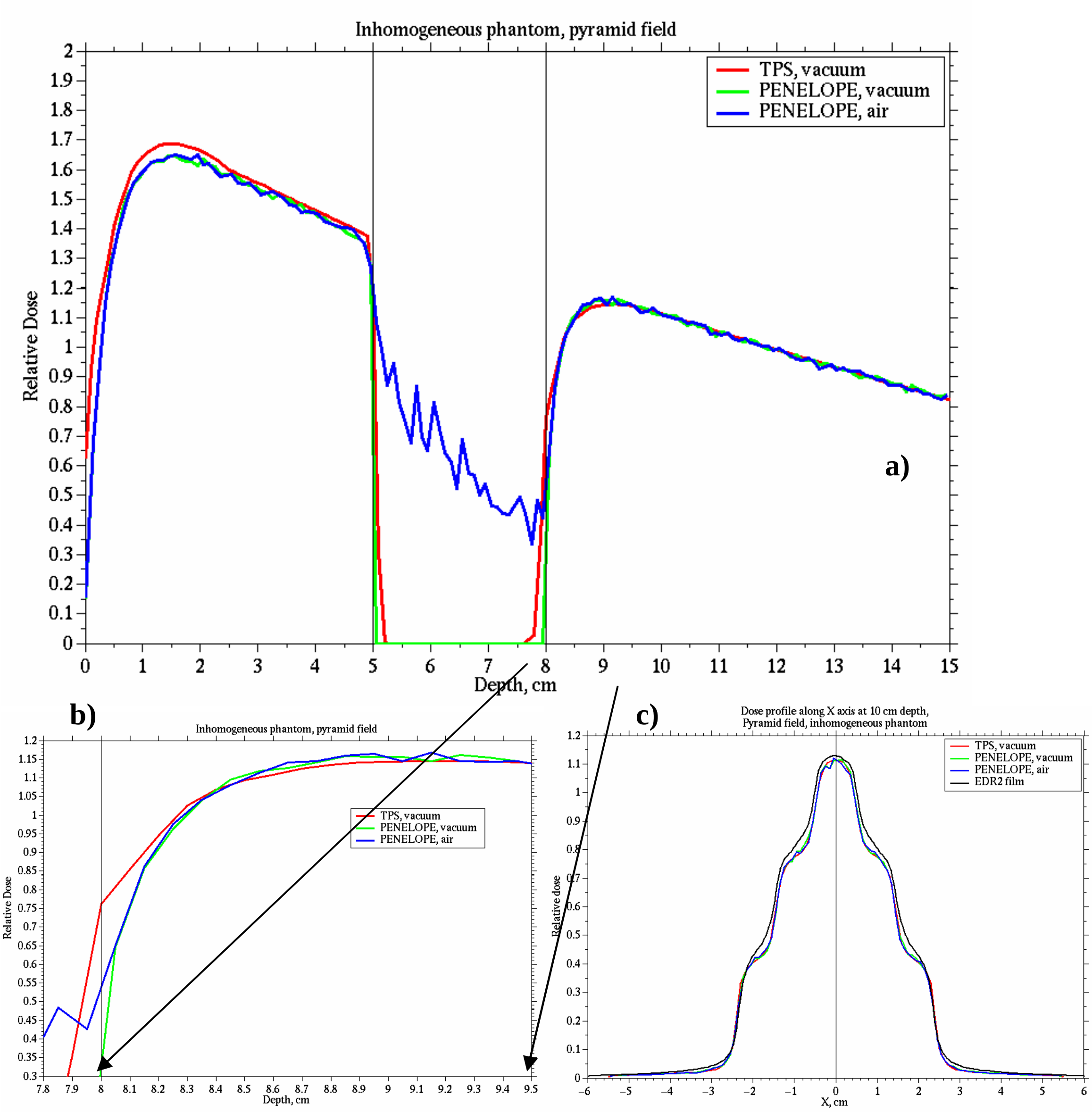

Figure 2. Dose profile along X axis relative to the dose at depth of 10 cm along the X axis in a homogeneous phantom calculated with MC code PENELOPE (blue, green), Commercial TPS superposition algorithm (red), and measured with EDR2 film (black). in an <u>inhomogeneous</u> phantom with 3 cm air/vacuum slab cavity at depth 5cm) a) and b) along the central axis and c) perpendicular to the central axis at a depth of 10 cm

2 CONCLUSIONS

During the treatment planning stage of the radiation therapy, dose calculation accuracy is among the most important objectives. The continued efforts to improve the dose calculation accuracy are focused on implementing MC algorithms and on reducing calculation time associated with them. We propose potential improving the quality of dose distribution and reducing the calculation time by joining the high speed of calculating phase space with a planning system and the detailed dose distribution obtained with a MC algorithm.

The ability of MC to account accurately for the perturbation of the particle transport through inhomogeneities could result in calculating of more accurate dose distribution with MC code such as PENELOPE than with superposition algorithm. Since the location, shape, and content of inhomogeneity affects the magnitude of charged particle disequilibrium there could be a number of clinical cases where the use of MC could be helpful. In the case of rectangular solid water phantom we obtained, though, that MC and treatment planning system produce practically identical dose distributions both for homogeneous and inhomogeneous setups.

In the regions far from inhomogeneities the measured dose was close to the dose calculated by TPS and MC showing that the MC algorithm works well when initial parameters are taken from the fluence map. The difference between the measured dose and the doses calculated with TPS and MC algorithms from the identical fluence maps is possibly to be mainly because of the approximation of the initial direction of the particles.

The next step could be directed toward investigation of the difference in dose distributions between TPS and PENELOPE for clinical setups of the treatment of actual patients in order to verify how the proposed algorithm could further benefit the outcome of the treatment.

3 ACKNOWLEDGMENTS

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