Benchmark of MCNP6 for ionization chamber simulation in the presence of a magnetic field using the Fano cavity theory: Dose comparison with EGSnrc, PENELOPE, and Geant4

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1. Introduction

The Monte Carlo simulation has been successfully applied to radiation transport in clinical dosimetry. Recently, radiotherapy machines integrated with simultaneous magnetic resonance image has been developing by several medical device companies. In the presence of a magnetic field, electrons set in motion by the Lorentz force, though photon beams were not affected so that dose calculation and measurement in the presence of a magnetic field should be validated.

The reference dosimetry was performed using an ionization chamber, which contains air cavity volume. Dose distribution of air cavity in an ionization chamber with external magnetic field was unknown. Recently, ionization chamber responses are found to vary by several percent in the presence of a magnetic field compared to the 0 T.

Currently, EGSnrc, PENELOPE, Geant4, and MCNP6 codes support charged particle transport in external magnetic fields. Several studies showed the feasibility of EGSnrc, PENELOPE, and Geant4 codes, but there is no study for MCNP6 code [1-5]. In this study, MCNP6 code is validated by a new Fano cavity test that accommodates an external magnetic field. Furthermore, each codes are compared with the other code.

2. Materials and Methods

For charged particle transport with external magnetic field, the recent version of each Monte Carlo code was used. MCNP 6.1, EGSnrc-master, PENELOPE 2014, and Geant4-10.3 were installed in personal computer or workstation.

2.1 Simulation Geometry

The Fano theorem has been used as an accuracy test of Monte Carlo algorithms. In order to perform the test for a Monte Carlo code, an artificial gas cavity region with a density 1000 times lower than the surrounding wall is made. The wall material was graphite with a density of 1.7 g/cm^3, and a density of gas material was 0.0017 g/cm^3. Three layered cylinder shape which contains a gas region inside of top and bottom side of wall regions was made. The radius of this geometry was set equal to the continuous slowing down approximation (CSDA) range of an artificial gas multiplied by a factor of 1.4 because of electron energy straggling. The height of the wall region was the CSDA range of the wall multiplied by a factor of 1.4. The height of gas region was 0.2 cm, similar to plane-parallel ionization chamber. Electrons with initial kinetic energy equal to 0.01, 0.1, 1, and 10 MeV were generated in the wall and gas with a uniform intensity per unit mass. By using the reciprocity theorem, a thin source of electrons was employed in the center of the geometry (Fig. 1.).

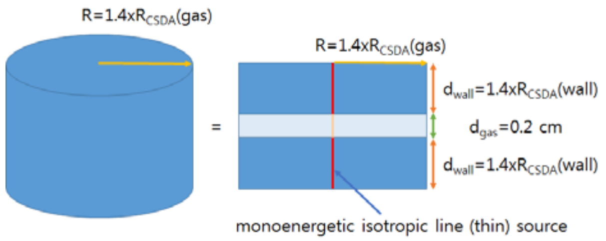

Fig. 1. The geometry for Monte Carlo simulation of each codes for the test of the Fano cavity theory.

2.2 MCNP6.1

F6 tally was generated in the gas region for dose calculation. It was equivalent to *F8 tally. For the accuracy test of an ionization chamber simulation with no magnetic field, the energy grid resolution parameter, *efac*, varies with several values. *efac* specifies the stopping power energy spacing. The default value of *efac* is 0.917. It means that each electron step corresponds to a fractional energy loss of 8.3%. We set 0.81, 0.87, 0.917, 0.93, and 0.99 of *efac* values. For accurate electron dose calculation, ITS-style of electron energy indexing was used.

2.3 EGSnrc-master

An EGSnrc user code, egs_chamber was used for cavity simulation. For the artificial gas material, a new cross section file called pegs4 was generated. The density of this gas was 1000 times less than that of the wall, but the same cross sections including the density effect was applied to the pegs4 file.

With no magnetic field, the ESTEPE value, which sets the maximal fractional energy loss, was varied from 0.01 to 0.25 to determine the step-size effects. In the presence of a magnetic field, EM ESTEPE (δ), a limit on the fractional change of the direction of motion produced by the magnetic field, was varied from 0.01 to 0.40.

$$s = \delta \cdot \frac{E_0 \gamma_0 \beta^2}{q(\vec{v_0} \times \vec{B_0})} = \delta \cdot r_g \quad (1)$$

s is the restricted step size, and the quantity r_g is the radius of gyration of the particle's trajectory.

2.4 PENELOPE 2014

The cutoff angle that separates hard from soft elastic interactions, C1 and C2, and the cutoff energies for the production of hard inelastic and bremsstrahlung events, WCC and WCR can be varied for the Fano cavity test. When all of C1, C2, WCC, and WCR are set to zero, a completely analogue simulation is achieved. In order to benchmark PENELOPE code, C1=C2=0.02 and WCC=WCR=0 were set with no magnetic field condition.

2.5 Geant4-10.3

Geant4 reference physics model (QGSP_BIC_EMY) was used. For multiple scattering, G4UrbanMscModel was selected. The parameter, *dRoverRange*, which set the energy loss step limitation, was set to 0.2, and the maximum range variation per step, *finalRange*, was set to 1 mm. G4KleinNishinaModel was used for Compton scattering.

3. Results

In MCNP 6.1, the results of the default *efac* value (0.917) was 1% of accuracy with no magnetic field for the initial energy of 0.01 and 0.1 MeV. When *efac* equals 0.99, the differences in MCNP 6.1 compared to the Fano cavity theory were within 0.7% (Fig. 2.). With a 1.5 T of magnetic field, accuracy was decreased compared to the results of no magnetic field. The default *efac* value cannot be satisfied with 1% of accuracy when the initial energy of electrons exceeds to 0.1 MeV (Fig. 3.).

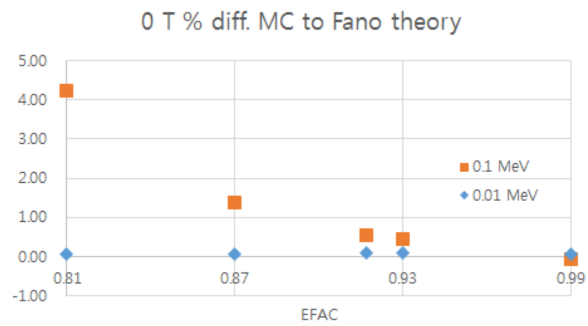

Fig. 2. The percent difference in MCNP 6.1 results compared to the Fano cavity theory with no magnetic field (0 T).

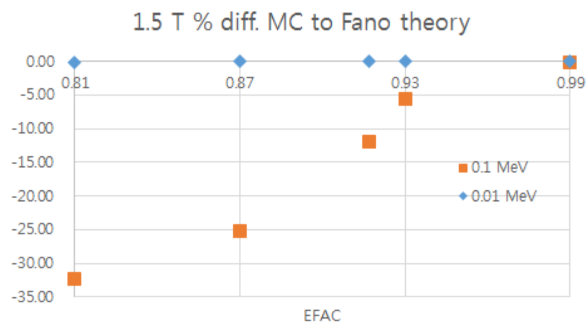

Fig. 3. The percent difference in MCNP 6.1 results compared to the Fano cavity theory with a 1.5 T magnetic field.

In EGSnrc, especially egs_chamber, the default ESTEPE (0.25) showed 0.1% of accuracy in all of the initial electron energies with no magnetic field (Fig. 4.). With a 1.5 T of magnetic field, the default value of EM ESTEPE (0.02) showed 1.5% of accuracy. When EM ESTEPE equals 0.01, the accuracy was increased by 0.6% (Fig. 5.).

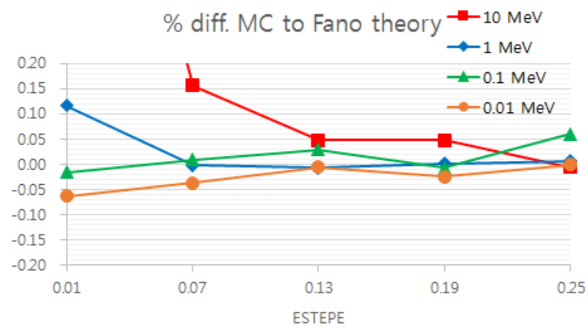

Fig. 4. The percent difference in EGSnrc results compared to the Fano cavity theory with no magnetic field (0 T).

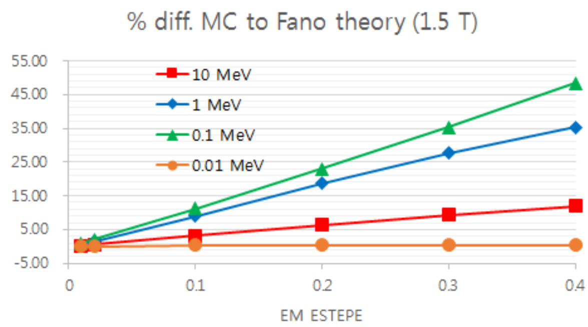

Fig. 5. The percent difference in EGSnrc results compared to the Fano cavity theory with a 1.5 T magnetic field.

In PENELOPE 2014, 0.4% of accuracy was acquired when the initial electron energy was 1 MeV with no magnetic field simulation (Fig. 6.).

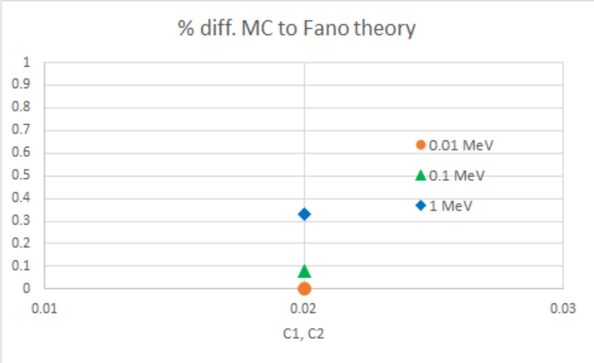

Fig. 6. The percent difference in PENELOPE 2014 results compared to the Fano cavity theory with no magnetic field (0 T).

In Geant4-10.3, Only 0.01 MeV of electron incident energy was simulated. 0.2% of accuracy was acquired with the default *dRoverRange* and *finalRange* Further simulations are needed to compared with the other codes.

4. Conclusions

Charged particle transport in magnetic fields has been implemented in four Monte Carlo codes, MCNP6, EGSnrc, PENELOPE, and Geant4 for high accurate calculation of ionization chamber in a phantom. This magnetic field implementation has been validated by the Fano cavity test. The expected accuracy of MCNP 6.1 was within 0.3% when *efac*=0.99, and egs_chamber showed 0.6% of accuracy when EM ESTEPE=0.01. For the accurate dose calculation of an ionization chamber using a Monte Carlo code, users should carefully handle physical parameters in each Monte Carlo code. PENELOPE 2014 and Geant4-10.3 can be also implemented in charged particle transport in a magnetic field, and more calculations are needed for whole comparison.

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