

## Monte Carlo code comparison of dose delivery prediction for Microbeam Radiation Therapy

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**Abstract.** Preclinical Microbeam Radiation Therapy (MRT) research programs are carried out at the European Synchrotron Radiation Facility (ESRF) and at a few other synchrotron facilities. MRT needs an accurate evaluation of the doses delivered to biological tissues for carrying out pre-clinical studies. This point is crucial for determining the effect induced by changing any of the physical irradiation parameters. The doses of interest in MRT are normally calculated using Monte Carlo (MC) methods. A few MC packages have been used in the last decade for MRT dose evaluations in independent studies. The aim of this investigation is to provide a preliminary basis to perform a systematic comparison of the dose results obtained, under identical irradiation conditions and for the same scoring geometries with the following five MC codes: EGS4, PENELOPE, GEANT4, EGSnrc, and MCNPX. Dose profiles have been calculated in an in-depth region of cylindrical phantoms made of water or PMMA. Beams in both cylindrical and planar geometry have been considered. This comparison shows an overall agreement among the different codes although minor differences occur, which need further investigations.

### 1. Introduction

X-ray microbeam radiation therapy (MRT) is a preclinical radiotherapy technique being explored at several facilities around the world and based on the use of arrays of X-ray microbeams with a mean energy of approximately 100 keV [1]. The MRT research programs carried out at the ESRF include both experimental (tissue sparing and curing effects with animals) and theoretical (Monte Carlo dosimetry) activities. Monte Carlo (MC) calculations are of fundamental importance for accurate evaluations of the doses delivered to a target volume and to the crossed healthy tissues, considering

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that experimental dose measurements with micrometric spatial resolution are still a challenging issue. The evaluation of these doses and their dependency on the geometrical parameters of the microbeam array, such as beam spacing and dimensions, is crucial for optimizing the conditions of the possible future clinical treatment planning. Previous studies [2,3,4] have highlighted the importance of the peak-to-valley dose ratio (PVDR) as a quality parameter for determining the efficiency of the MRT technique in cancer treatment. For a correct evaluation of the PVDRs it is necessary to calculate the profiles of the delivered doses, at different depths into biological phantoms, with micrometric spatial resolution.

The MC packages commonly used for dose evaluation purposes have been originally conceived to perform calculations for radiation beams of high energy (MeV) and extended dimensions ( $\text{cm}^2$ ). A large effort has been made over the last 15 years to improve their performances for low X-ray and electron energies which are relevant to medical applications. These MC packages deal with the radiation transport basing on different approaches. Moreover, photon and electron interaction cross sections are generally retrieved from different databases. These differences can explain some discrepancies in the results obtained in some independent studies which can be found in the literature [3]. Aim of this work is to provide an initial basis for a systematic comparison of the doses calculated by five selected and commonly used MC packages, under identical, well defined conditions, starting from simple irradiation and scoring geometry.

## 2. Method and Materials

The following five MC codes were selected for the comparison: EGS4 with the modern low energy extensions LSCAT and PRESTA [5], PENELOPE [6], MCNPX [7], EGSnrc [8] and GEANT4 with the PENELOPE extension [9].

The chosen geometry is the simplest possible for the comparison. Two standard cases were selected for the beam shape: cylindrical and planar shape. The source of the monoenergetic unpolarized photons beam is placed at the origin of the reference system and the primary photons wave-vector is in the (0,0,1) direction.

The energy cut-off threshold, under which the transport of the particles is stopped, is 1 keV for both photons and electrons. The primary photons histories simulated are  $10^7$  and no variance reduction technique has been used. The photons have been evenly distributed and we have not considered any angular divergence of the beam.

In the first part of our study a cubical water (density  $1.0 \text{ g/cm}^3$ ) volume of  $10^3 \text{ cm}^3$  has been chosen as a phantom and transversal dose profiles for a  $25 \text{ }\mu\text{m}$  diameter cylindrical beam were calculated at different depths and energies in the phantom. This was done in order to compare both the absolute dose values and their profiles as a function of the distance from the X-ray beam central axis. Monoenergetic beams of 50keV, 100keV and 150 keV have been used for the cylindrical beams to facilitate the physical analysis of the calculated profiles.

In the second part of the study, the dose distributions, produced by narrow rectangular beams (so called planar beams), were calculated in a PMMA phantom. The same kind of dose profiles as for the cylindrical beams were calculated. The planar beams are typically used in MRT experiments and therefore the related results can give some important indications for future clinical tests. For the simulations of the dose profiles produced by the planar beams, the X-ray energies have been sampled from the measured source spectrum of the ESRF medical beamline (ID17).

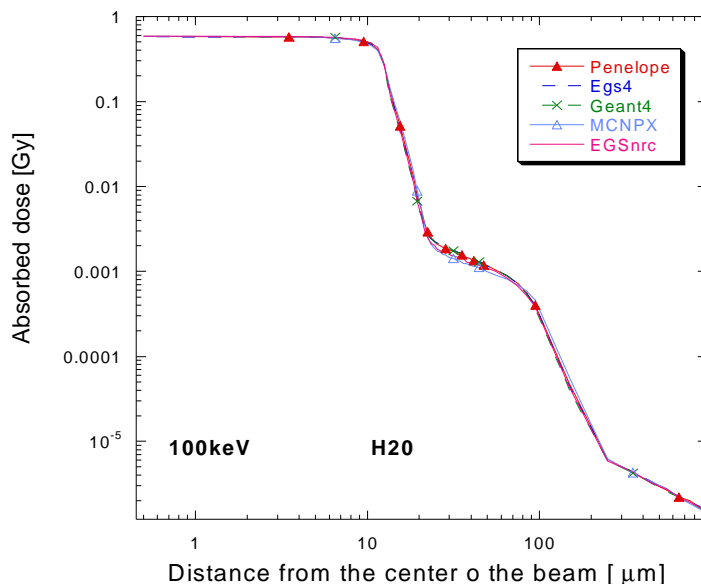
Due to space limitations, only a few representative results have been selected and presented here.

### 3. Results and conclusion

#### 3.1 Cylindrical microbeam

For the cylindrical beam geometry the calculations of the radial profiles spanned a 1 cm radial distance from the microbeam center. In order to obtain statistically significant results the doses were integrated over 1 cm thick circular bins centered at 7.5 cm below the entrance surface of the phantom. The following radial bin widths were used: 1  $\mu\text{m}$  in the radial range 0-50  $\mu\text{m}$ ; 10  $\mu\text{m}$  in the radial range 50-100  $\mu\text{m}$ ; 100  $\mu\text{m}$  in the radial range 100-1000  $\mu\text{m}$  and 1 mm in the radial range between 1 mm and 1 cm.

The results are presented in figure 1 for a 100 keV monoenergetic beam and for 25  $\mu\text{m}$  diameter beam size. The profile is displayed in a log-log scale in order to show clearly the entire dose profile. The depth of 7.5 cm was chosen for scoring the dose because it has been used as a reference depth since the beginning of MRT. Actually, such a depth is meant to be representative for the middle portion of the human head.

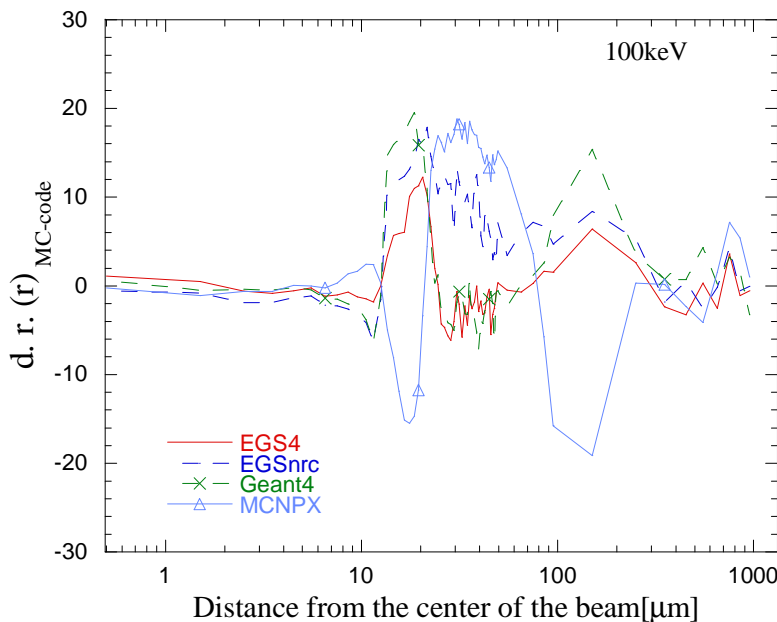


**Figure 1.** Transversal dose profiles at 7.5 cm depth in water for a 25  $\mu\text{m}$  diameter cylindrical beam. The beam energy was set to 100 keV in the simulations.

Since the differences between the transversal dose profiles are not evident in the graph, an additional calculation of dose-difference ratios (with PENELOPE arbitrarily chosen as a reference term) was performed in order to highlight any dissimilarity. The result of this calculation is shown in figure 2. The difference ratios (d.r.) were calculated using the following expression:

$$d.r.(r)_{MC-code} = \frac{Dose(r)_{MC-code} - Dose(r)_{PENELOPE}}{Dose(r)_{PENELOPE}} \cdot 100 \quad (1)$$

where  $Dose(r)_{MC-code}$  is the dose at a radial distance  $r$ , as calculated by any of the five MC codes.

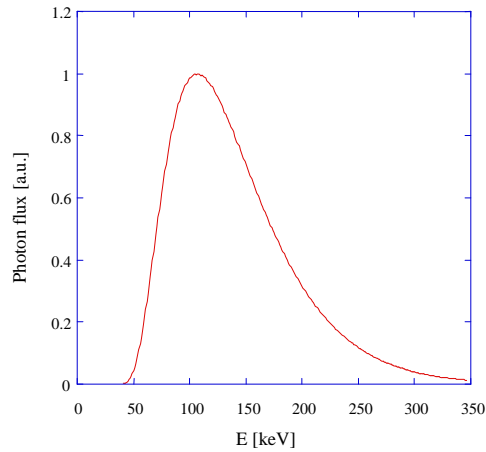


**Figure 2.** The difference ratios calculated using (1) for the dose profiles of figure 1.

As shown in figure 2 the largest profile differences compared to the PENELOPE calculations were stated for MCNPX: they do not exceed however  $\pm 20\%$  in a limited interval of distances (10-200 $\mu\text{m}$ ). Analogous results were obtained in the cases of incident photon energies of 50 and 150 keV. Since the mean energy of the ID17 source is about 100 keV, the curves displayed in figures 1 and 2 are clearly the most representative for our MRT study.

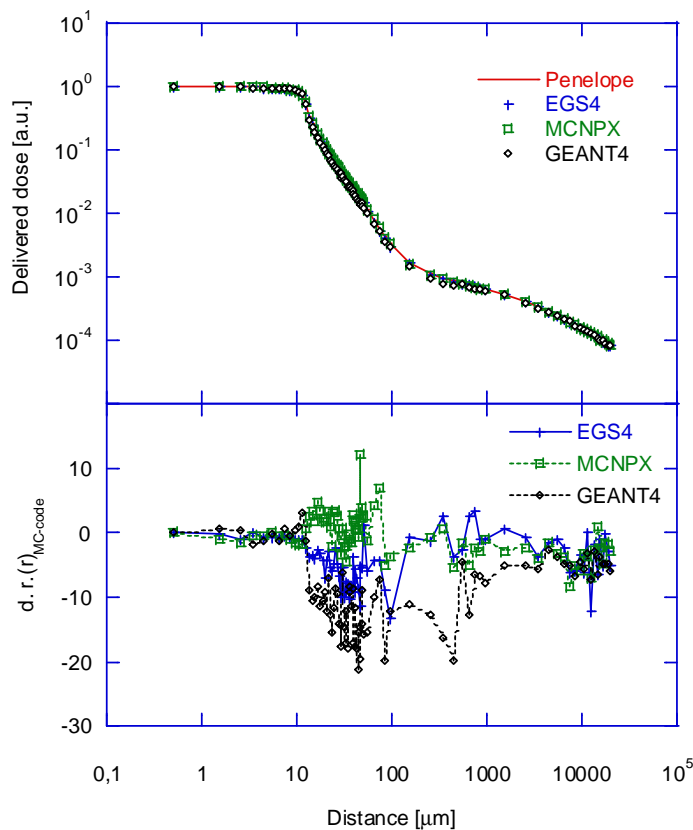
### 3.2 Planar microbeam

For the planar beam geometry the dose were scored at a depth of 7.5 cm below the entrance surface of a PMMA phantom using X-ray energies sampled from the ID17 experimental spectrum (figure 3). For this calculations the transversal dose profiles were determined up to 2 cm distance from the microbeam center and the beam size was assumed to be  $25 \mu\text{m} \times 1 \text{cm}$ . The doses were collected in 3-dimensional bins (parallelepipeds) over the full beam height (in the beam area, for example,  $1 \mu\text{m} \times 1 \text{cm} \times 1 \text{cm}$ ). The following transversal bin widths were used: between 0 and 50  $\mu\text{m}$ : 1  $\mu\text{m}$ ; between 50 and 100  $\mu\text{m}$ : 10  $\mu\text{m}$ ; between 100 and 1000  $\mu\text{m}$ : 100  $\mu\text{m}$ ; between 1 mm and 2 cm: 1000  $\mu\text{m}$ .



**Figure 3.** The experimental spectrum used for MRT studies at the ESRF ID17 beamline [10].

The transversal dose profiles at 7.5 cm depth are shown in figure 4 for EGS4, PENELOPE, MCNPX and GEANT4. The results obtained with these four codes have a general good agreement, and the largest difference results, not exceeding  $\pm 20\%$  in the distance range 10-1000  $\mu\text{m}$ , are produced by GEANT4.



**Figure 4.** (Top) Comparative dose profile results in PMMA at 7.5 cm depth for 25  $\mu\text{m}$  wide planar beams as obtained from the different codes and (bottom) percentage dose ratio calculated using (1). The microbeam X-ray energies have been sampled from the spectrum shown in figure 3.

The observed differences are limited to regions just outside of the primary photon beam in the region where the transport of the electrons is the dominating mechanism for the dose deposition. This seems to suggest that these differences depend on the electron transport modeling, which is a function of the used cross sections for the different electron-driven processes and of the different transport algorithms. Our comparison suggests that, at least for simple geometries and material compositions, the selected codes provide results matching one another within  $\pm 20\%$  accuracy.

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