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Computational Performances of ICRP Pediatric Mesh-type Reference Computational Phantoms in Geant4, MCNP6, and PHITS

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1. Introduction

The International Commission on Radiological Protection (ICRP) formulated Task Group 103 to develop the new mesh-type reference computational phantoms (MRCPs) by converting the existing voxel-type reference computational phantoms (VRCPs) into a high-quality mesh format. The MRCPs overcome the limitations of the VRCPs due mainly to restricted voxel resolutions and the natural of voxel geometry. For example, the VRCPs encounter difficulties in defining micron-scale target and source regions within the skin, eye lens, alimentary and respiratory tract organs, and urinary bladder, the scales of which are below the size of voxels. On the other hand, the MRCPs in tetrahedral-mesh (TM) format can effectively represent such thin/small regions and can be directly implemented in the general-purpose Monte Carlo codes such as Geant4, MCNP6, and PHITS without voxelization process.

The MRCPs consist of several millions of tetrahedra to define the detailed anatomical structure and, therefore, require considerable memory usage and run times for dose calculations. Following the development of the adult MRCPs in ICRP *Publication 145*, our previous study investigated the computational performance (i.e., implementation time, memory usage, and run time) of using MRCPs in Geant4, MCNP6, and PHITS [1]. Recently, pediatric MRCPs have also been developed, and ICRP Publication for the phantoms is currently under preparation. Thus, in the present study, the computational performance was further assessed by implementing the pediatric MRCPs in the recent version of Geant4 (version 11.01.p02), MCNP6 (version 2.0), and PHITS (version 3.31).

2. Methods and Results

The pediatric MRCPs consist of newborn, 1 year, 5 years, 10 years, and 15 years-old males and females and define all the organs and tissues required for effective dose calculation. The pediatric MRCPs are in the TM format and can be directly implemented in the Monte Carlo codes such as Geant4, MCNP6, and PHITS. The number of tetrahedra for each phantom can be found in Table 1.

Table 1: Number of tetrahedra for pediatric mesh-type reference computational phantoms (MRCPs)

Number of tetrahedra	Male	Female
newborn	7,556,192	7,650,261
1-year-old	6,715,301	6,943,945
5-year-old	8,178,096	8,440,293
10-year-old	6,922,345	7,097,644
15-year-old	7,337,331	7,503,866

The pediatric MRCPs were implemented in Geant4 (version 11.01.p02), MCNP6 (version 2.0), and PHITS (version 3.31) to assess the computational performance in terms of implementation time, memory usage, and run time. Computational performance was measured on a single core of the Intel® Xeon® CPU E5-2698 v4(@ 2.20 GHz CPU processor) equipped with 256 GB random access memory (RAM) in CentOS 7 Linux. Run time was measured for photons and electrons for external broad parallel beam in anterior-posterior (AP) irradiation geometry from 10^{-2} to 10^{4} MeV by simulating 10^{6} primary particles. The simulations were repeated 10 times to minimize the errors related to computational performance. The physics library of *G4EmLivermorePhysics* was used for the transportation of photons and electrons for Geant4. The default physics libraries from Lawrence Livermore National Laboratory evaluated data were used for MCNP6, and the *EGS5* physics library was used for PHITS. For Geant4, the range of 1 μm was used for the secondary production cut, and the equivalent energy cut-off value (= 1 keV) was used for MCNP6 and PHITS.

3. Results and Discussion

3.1 Comparison of organ doses

Figure 1 shows the calculated organ doses of the 1-year-old female MRCP as an example for photons and electrons in the AP irradiation geometry. It can be generally seen that a good agreement was observed for all the energy ranges among the different codes. The differences are all less than 1.3%. The dose results confirm that the phantom was correctly implemented in the Monte Carlo codes.

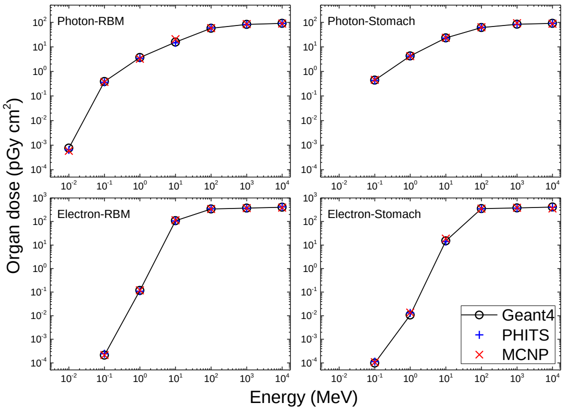

Fig. 1. Red bone marrow (RBM) and stomach doses of 1-year-old female mesh-type reference computational phantom (MRCP) in antero-posterior (AP) irradiation geometry for Geant4, MCNP6, and PHITS.

3.2 Evaluation of implementation time and memory usage

Table 2: Implementation time and memory usage of pediatric mesh-type reference phantoms (MRCPs) in Geant4, MCNP6, and PHITS

		Implementation time (min)			Memory usage (GB)		
		Geant4	MCNP6	PHITS	Geant4	MCNP6	PHITS
newborn	M	3.89	2.00	0.603	13.3	3.79	1.46
	F	3.97	2.01	0.605	13.2	3.84	1.46
1-year-old	M	4.30	1.86	0.624	13.5	3.42	1.37
	F	4.39	1.91	0.628	13.6	3.50	1.61
5-year-old	M	4.08	2.17	0.679	13.7	4.10	1.56
	F	4.08	2.23	0.684	13.6	4.22	1.60
10-year-old	M	4.07	2.00	0.678	13.2	3.62	1.47
	F	4.03	1.97	0.687	13.1	3.55	1.46
15-year-old	M	3.93	2.03	0.670	12.4	3.73	1.50
	F	4.04	2.07	0.668	13.0	3.81	1.52

Table 2 shows the implementation time and memory usage of the pediatric MRCPs in Monte Carlo codes. It can be seen that for both the implementation time and memory usage, PHITS showed the shortest time and the smallest memory usage while Geant4 showed the longest time and the largest memory usage; the maximum differences were 7 times for the implementation time for the 1-year-old female MRCP and 9.9 times for the memory usage for the 1-year-old male MRCP. The results indicate that the pediatric MRCPs can be used in a personal computer with 16 GB memory even for Geant4. Note that the low memory requirement for PHITS is due to the dynamic allocation of the memory space for PHITS.

3.2 Evaluation of run time

Figure 2 shows the run time of the 1-year-old female MRCP as an example in the AP irradiation geometry for Geant4, MCNP6, and PHITS. Geant4 showed the shortest run time for all the cases, which means that the calculation speed of Geant4 is faster than the other codes. On the other hand, MCNP6 showed the longest run time, the maximum difference between Geant4 and MCNP6 was 71 times for electron at 10^4 MeV. The poor performance of MCNP6 seems due to the fact that the MCNP6 uses unstructured mesh (UM) geometry, which is overly sophisticated in defining the simple TM geometry, while the other codes use TM geometry-dedicated particle transport algorithm. Nevertheless, considering that the run time took only a few days even for MCNP6 with a single core CPU, the run time is expected to be within a few hours when the simulation is performed in a multithreading and multiprocessing machine [4].

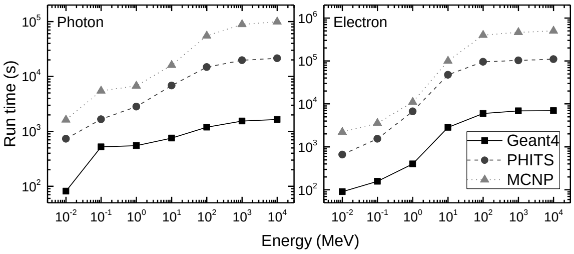

Fig. 2. Run time of 1-year-old female mesh-type reference computational phantom (MRCP) for photons and electrons in anterior-posterior direction for Geant4, MCNP6, and PHITS.

4. Conclusion

In the present study, the ICRP pediatric MRCPs in a TM format were implemented in Geant4, MCNP6, and PHITS to assess the computational performances in terms of implementation time, memory usage, and run time. Implementation time and memory usage were found to be most demanding for Geant4 but were still fine for use on a personal computer. For run time, Geant4 showed the fastest calculation speed for both the external and internal exposures while the MCNP6 showed the slowest calculation speed. These results are mainly due to the use of TM geometry-dedicated transport algorithm. Coupled with multi-threading and multi-processing features, the pediatric MRCPs are expected to be able to estimate radiation doses within reasonable time with all Geant4, MCNP6, and PHITS codes. In addition, given the ongoing optimization of TM geometry-dedicated algorithms in many Monte Carlo codes (e.g., egs_mesh library in EGSnrc [5] and TM geometry implementation time and memory usage optimization in the upcoming MCNP6.3 release [6]), the computational performance for the tetrahedral-mesh geometry are expected to be further improved in the near future.

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