Optimization of Patient Geometry Based on CT Data in GEANT4 for Medical Application

Tsukasa Aso, Akinori Kimura, Tomohiro Yamashita, and Takashi Sasaki

***Abstract*—The GEANT4 Monte Carlo code provides many powerful functions for conducting particle transport simulations with great reliability and flexibility. GEANT4 has been extending the application fields for not only the high energy physics but also medical physics. In radiation therapy, patient data are usually given in DICOM format and have to be imported into a simulation as geometry. For this purpose, a DICOM interface has been developed for retrieving CT data from DICOM files and converting it into suitable format for making geometry. The GEANT4 defines a patient geometry as a series of voxels. The "parameterized volumes" in GEANT4 is capable to deal with such voxelized geometry. Alternatively, more efficient functionality, "nested parameterization volumes" has been introduced since GEANT4 version 8.1. The performances of these functionalities have been studied in terms of computational efficiency about a patient geometry of a series of voxels with GEANT4 version 8.2 and 9.0. The functionality of the DICOM interface and the result of the performance study have been reported in this paper. The dramatic improvement of memory consumption has been confirmed by adopting the "nested parameterization volumes" instead of normal "parameterization volumes".**

***Index Terms*—GEANT4, Monte Carlo, Dose calculation, Radiotherapy, DICOM**

I. Introduction

Many techniques for radiation therapy are being developed for a cancer treatment. In such radiation therapy, Monte Carlo method has been widely adopted to the way of precise dose calculation. GEANT4 toolkit [1] provides many powerful functions for conducting simulation of particle passing through and interacting with matter with reliability and flexibility. The GEANT4 was originally assumed for use in high energy physics, but it has also demonstrated its wide applicability in medical physics. The verifications of GEANT4 in dose calculation for nozzle design and quality assurance for radiation therapy facility had been already reported in [2]–[4]. The next interest is the simulation with patient data like a treatment planning system where computational efficiency is especially critical.

In radiation therapy facilities, patient data are usually given as CT data in DICOM format [5] and have to be imported into the simulation as geometry. This requires a DICOM interface and a geometry builder in order to get CT data in DICOM format and make the patient geometry. The GEANT4 can define the complex patient geometry according to CT data as a series of voxels i.e. cubic boxes using "parameterized volumes" where the materials are parameterized in function of the copy number and dynamically assigned to the volume. We have developed a DICOM interface and a geometry builder to make a patient geometry from CT data [6]. However, it is not easy to achieve statistically reliable dose calculations on patient data in reasonable time and memory size, because the number of voxels to form a patient geometry is enormous. In order to address to this requirement from medical application, the more efficient functionality "nested parameterization volumes" has been additionally introduced by GEANT4 collaboration since version 8.1 [7].

In this report, we describe the functionality of our DICOM interface and the performance study of a patient geometry based on CT data in GEANT4 by comparing these different parameterization methods. The effect of recent upgrade in GEANT4 from version 8.2 to 9.0 is also mentioned at the point of the performance in the geometry defined by a series of voxels.

II. Simulation with Patient Geometry

A. DICOM Interface and Geometry Builder

Patient CT data are usually given in DICOM format in radiation therapy. The CT data have to be imported into a simulation as geometry. We have developed DICOM interface based on the example code provided with GEANT4. But we redesigned the DICOM interface to have more capability for handling DICOM format so that our DICOM interface becomes completely different from the original GEANT4 example. Our DICOM interface converts CT data into suitable format for making geometry in the simulation. The developed DICOM interface can handle DICOM-RTX [5] as well as standard DICOM format, where DICOM-RTX is one of extensions of DICOM-RT which includes parameters for settings a irradiation system such as multi-leaf positions.

Our DICOM interface can retrieve CT data from various manufactures' DICOM files [6]. The class diagram of our DICOM interface is shown in Fig. 1. The class G4MDICOMHandler reads information from DICOM files using a DICOM dictionary and stores it in an object of a class G4MDICOMConfiguration. The object has two storage objects of classes G4MDICOMTagInfo and G4MDICOMData in which tag information and CT data are stored, respectively. The class G4MVDICOMFilter is a base class for converting the original CT data to suitable format for making geometry.

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We provide concrete filters such as compensating lack slices, extracting actual patient volume by removing surrounding air voxels by specifying a cut off CT value, converting CT data to corresponding densities, and reforming the pixel spacing with user-defined arbitrary size. Here the averaged Hounsfield Unit values are calculated by using a tri-linear interpolation and trapezoidal integration method in the reformation of the pixel spacing. These filters are plugged into an object of class G4MDICOMConfiguration as modules. Fig. 2 shows examples of converted images by using these filters. By applying these filters such as extraction of actual patient volume and reformation of pixel spacing, the reduction of number of voxels in the patient geometry is expected. The class G4MDICOMManager is a singleton class for accessing a DICOM handler object and DICOM configuration objects so that users are able to retrieve DICOM information in the simulation code.

The patient geometry in GEANT4 is then defined by a geometry builder as a series of cubic boxes for making geometry. The geometry builder prepares materials corresponding to Hounsfield Unit values in CT data and constructs a patient geometry with voxels. There are a couple of choices for material variations which are nine representative materials in tissues or waters of different densities with respect to Hounsfield Unit values. The former case is provided for simple test of the simulation.

In this study, we used CT data of a plastic phantom taken at Hyogo Ion Beam Medical Center [8]. It has 512×512 pixels and 208 slices in the original format so that the total number of voxels is about 55M voxels. Because our study is not focused on validating the dose distribution but on performance study about the patient geometry defined by voxels, CT values were categorized into nine representative materials in tissues, in order to reduce memory consumption caused by the variation of materials.

B. Parameterization of voxels

In GEANT4, the one of the type for managing up to tens of millions of voxels is the "parameterized volumes". It is a single volume represents multiple copies of a volume. These multiple copies are allowed to be different in solid type, dimensions, and material. This is suitable for defining geometry of CT data. There is an argument, pAxis in "parameterized volumes", which specifies the tracking optimization algorithm to be applied. The pAxis gives the direction in which the parameterization is performed in a simple one-dimensional voxelization algorithm. On the other hand, if pAxis is specified as "kUndefined", the default three-dimensional voxelization algorithm is applied with normal placements. In the latter case, more voxels will be generated so that a greater amount of memory will be consumed by the optimization algorithm.

A more advanced alternative is the "nested parameterization volume". This enables a user to assign a material depending on the copy number of the parent volume. The parent volume can be a replicated volume which is expected to be faster for searching the tracking volume than the "parameterization volumes" as well as minimizing memory size. On contrast to the "parameterization volumes", the "nested parameterization volumes" requires volumes which shape and size are exactly same but only the material is different. By creating two levels of replicated parent volume, the "nested parameterization volumes" is possible to represent CT data as a patient geometry, while requiring only limited additional memory by very fine-level optimization.

TABLE I
MEMORY CONSUMPTION AND USER TIME FOR A HOMOGENEOUS WATER PHANTOM.

Type of geometry	Memory (KB)	User Time (sec.)
Replica	24	202
Parameterised (kUndefined)	994582	231
Parameterised (kZAxis)	27	15267
NestedPrameterisation	26	218

III. Results and Discussion

We studied computational efficiency in terms of memory consumption and execution time by comparing different voxelization schemes for a patient geometry. The simulations were carried out with 3 GHz Intel Xeon(x86_64) processor with 4 GB RAM by tracking protons from the entrance of a target geometry with respect to z-axis. Standard electro-magnetic processes and hadronic processes are chosen as a physics-list. The proton energy and the range cut were set to 100 MeV and 1 mm, respectively. The memory consumption and execution time were taken from the value of "ReportVoxelStats" of class G4GeometryManager and "user time" of run summary of standard output in GEANT4. It should be noted that the execution time does not include initialization time of the simulation.

A. Homogeneous Water Phantom

The influences of optimization algorithms had been studied with a homogeneous water phantom in GEANT4 version 9.0. The water phantom was divided into 101×101×250 voxels with 2 mm spacing. We compared "replicated volumes", "parameterized volumes" with kUndefined or kZAxis optimization, and "nested parameterization volumes". Here "kZAxis" represents the optimization along with z-axis. 10^5 primary protons were injected. The results are shown in Table I. The one dimensional optimization takes about 66 time longer execution time than the three dimensional optimization, while it can reduce the memory consumption to almost same size of "replicated volumes". This result indicates that the default three-dimensional optimization algorithm should be chosen for faster execution, while the huge amount of memory may be requested in "parameterised volumes".

B. Plastic phantom of DICOM format

The computational efficiency has been studied using CT data of a plastic phantom. The CT data originally has 512×512×208 voxels. However, about 75 % of those voxels are surrounding air voxels around the actual patient volume. In the simulation, these air voxels are identified by specifying the cut off of CT value in our DICOM interface. These air

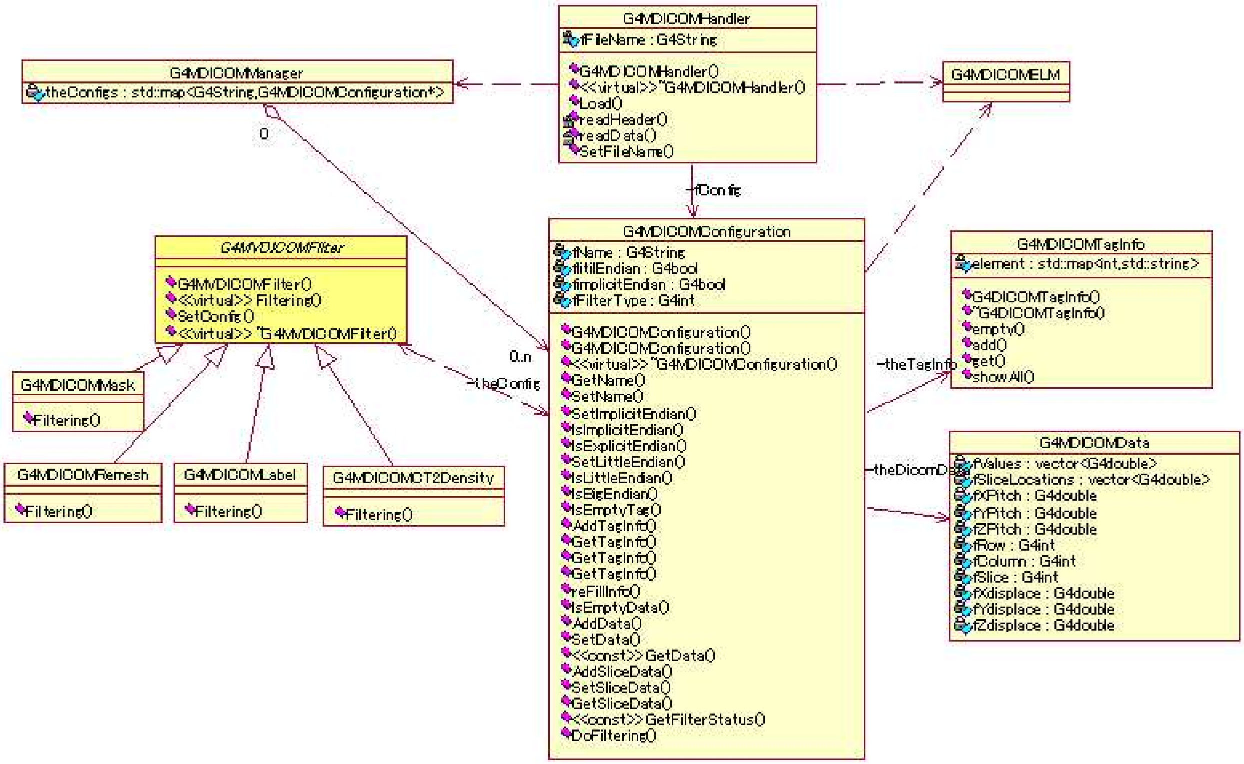
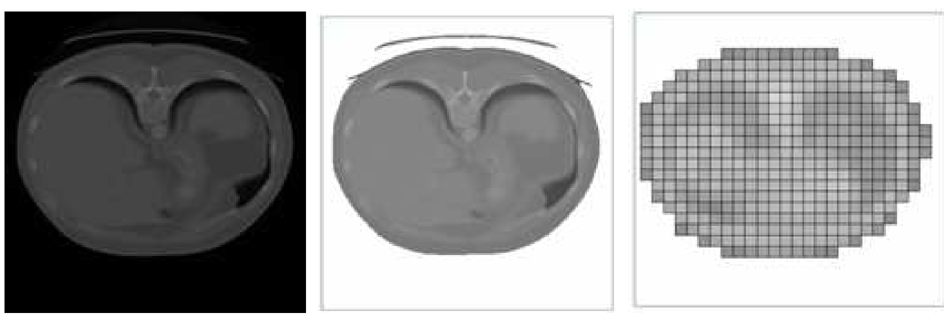


Fig. 1. Class diagram of developed DICOM interface.



(a) Original CT image.

(b) Removing air pixels from the original CT image.

(c) Reforming the pixel spacing.

Fig. 2. Example images for demonstrating filters which convert a original CT image to suitable format for making geometry.

voxels surrounding the actual patient volume were removed from geometry in “parameterised volumes” of extract mode , while these are placed as air voxels in “parametrised volumes” and “nested parameterisation volumes”. Our DICOM interface is able to reforming pixel spacing with user-defined arbitrary size so that the number of voxles is reduced by choosing longer size of pixel spacing. These techniques for reducing number of voxels are expected to improve computational efficiency. The effects of voxelization schemes in GEANT4 have been studied for “parameterised volumes” with “kUndefined” optimization and “nested parameterisation volumes”. Here “parameterised volumes” are tested by placing whole volumes (“Extract” mode in the results) or only actual patient volume in CT data. 2×10^5 primary protons were simulated.

Fig. 3 shows the result of memory consumption as a function of number of voxels of the geometry. Here the GEANT4 is version 8.2. No significant differences had been observed between GEANT4 version 8.2 and 9.0. In dependent to the versions, the result clearly shows that “nested parameterisation volumes” suppresses the memory consumption dramatically.

Fig. 4 and Fig. 5 show the results of execution time of event processing in GEANT version 8.2 and version 9.0, respectively. In version 8.2, the execution time takes longer if only the patient volume is extracted from CT data and only placed as geometry. However this tendency is clearly improved in version 9.0. The longer execution time in version 8.2 is caused by the interference between electron’s multiple scattering process and a navigator inside GEANT4. A class

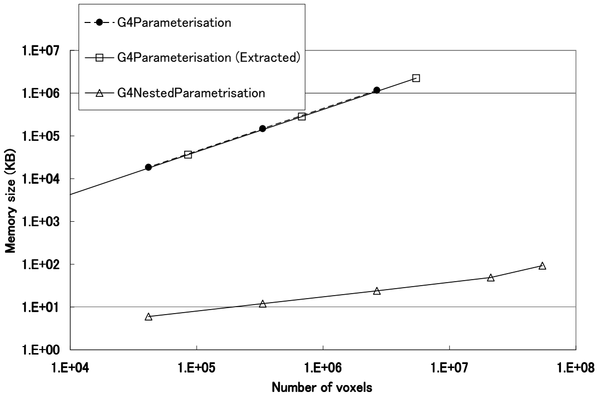


Fig. 3. The memory size as a function of number of voxels in a patient geometry with GEANT4 version 8.2. Here the optimization was specified with "kUndefined" in both "paramterised volumes". In extract mode, only the actual patient volume was placed as geometry by removing surrounding air voxels.

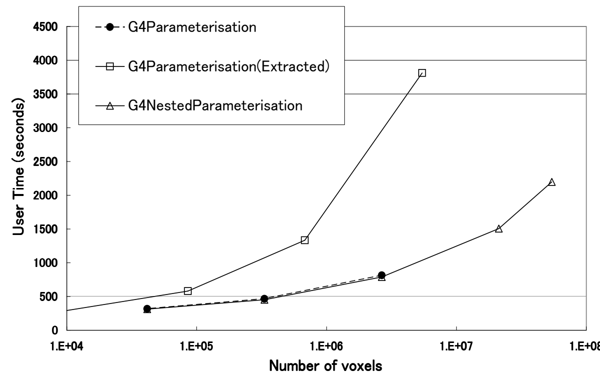


Fig. 4. Execution time as a function of number of voxels in a patient geometry with GEANT4 version 8.2. Here the optimization was specified with "kUndefined" in both "parameterised volumes". In extract mode, only the actual patient volume was placed as geometry by removing surrounding air voxels.

G4SafetyHelper had been introduced since version 8.3 for providing an efficient way to getting the safety length in a geometry instead of calling the navigator directly. This modification contributes to the improvement. Fig. 6 shows the comparison of execution time between version 8.2 and version 9.0. In "nested parameterisation volumes", the execution time of version 9.0 is about 20 % faster than that of version 8.2.

IV. Conclusion

We have studied about optimization of a patient geometry based on CT data using our developed DICOM interface and geometry builder. The "parameterization volumes" and "nested parameterization volumes" in GEANT4 have been tested in terms of computational efficiency. Since the developed DICOM interface is capable to deal with the CT data for modifying the pixel spacing and removing surrounding air voxels around the actual patient geometry, the performances have been studied on memory consumption and execution time as a function of number of voxels. We have confirmed that memory size is dramatically suppressed by adopting "nested parameterization volumes". The effect of the recent upgrades in GEANT4 are also confirmed to contribute for improving the execution time about 20 %.

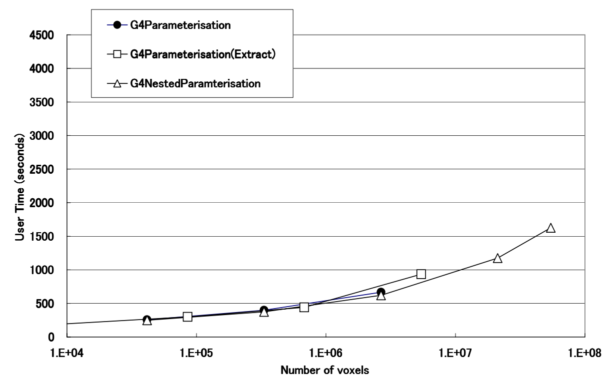


Fig. 5. Execution time as a function of number of voxels in a patient geometry with GEANT4 version 9.0. Here the optimization was specified with "kUndefined" in both "parameterised volumes". In extract mode, only the actual patient volume was placed as geometry by removing surrounding air voxels.

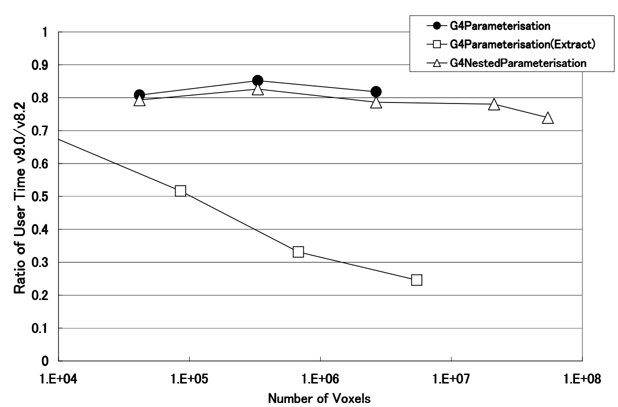


Fig. 6. Ratio of execution time of GEANT4 version 9.0 and 8.2 as a function of number of voxels in a patient geometry. In extract mode, only the actual patient volume was placed as geometry by removing surrounding air voxels.

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