

RESEARCH ON THE CONSTRUCTION OF A PHANTOM IN DOSE CALCULATION BY PHITS SIMULATION PROGRAM

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Abstract. In the field of medical physics, determining the dosage for organs is a very complex problem because it is impossible to directly measure the dosage inside a living person's body. Therefore, in order to estimate the dosage, one usually has to use phantoms. For dosage determination and safety assessment, Monte Carlo simulation programs and today's phantoms have become indispensable tools. There are already several standard phantoms in the world but they do not represent biological characteristics by region or for a specific object. Another method used to build characteristic phantoms is done through computed tomography (CT) images and the Hounsfield index. The method requires to convert the grayscale value of each pixel element into the Hounsfield index. As such, it can only be applied to CT imaging. To overcome this shortcoming, this study has developed a program based on a new process that can convert images to geometric format for MCNP/PHITS. The new procedure that we propose will allow researchers to describe the anatomical structures more accurately and be specific to each patient.

Keywords: phantom, PHITS, MCNP, CT/MRI, Hounsfield unit.

1. Introduction

The Monte Carlo simulation approach has become a vital tool for solving nuclear-related issues. The Monte Carlo method has been widely utilized to obtain useful information and very accurate findings from radiation movement models [1]. MCNP (Monte Carlo N-Particle Transport), PHITS (Particle and Heavy Ion Transport code System), EGS (Electron Gamma Shower), FLUKA (FLUktuierende KAskade), and GEANT4 (Geometry And Tracking 4) are examples of popular multi-purpose simulation programs based on the Monte Carlo approach. Programs for Monte Carlo simulation are commonly used in a wide range of applications, such as radiation protection, radiotherapy, and medical imaging [2]. Using human anatomical models to calculate radiation dose has long been a source of intrigue in the disciplines of radiation protection, medical imaging,

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and radiation therapy. For a multitude of reasons, determining the dose inside the human body is frequently hard and challenging, including: (1) because of the geometrical complexity between the source and the human body, many different irradiation situations can arise; (2) the irradiation process sometimes uses several types of radiation, each of which has properties and interacts with tissues via specific mechanisms; and (3) the human body is complex, consisting of heterogeneous anatomical structures of varying densities, sizes, shapes, and radiation sensitivities, and they are not stationary but subject to movement [3].

Because the dose inside a living person cannot be measured directly, anatomical models are critical in radiation dosimetry. As a result, phantoms are frequently used to estimate the dose. Computational phantoms based on human subjects play an important role in improving the efficacy of radiation treatments in radiotherapy [4]. Phantoms are classified into two types: physical phantoms and computer phantoms. Physical phantoms are composed of the usual human tissue equivalents of water, which are used in experimental dosimetry experiments. For Monte Carlo simulation codes, computer phantoms were created. These phantoms can show a lot of detail about the inside and outside of the human body, such as shape, density, volume, composition, and so on.

There are three types of computer phantoms: stylized phantoms, voxel phantoms, and boundary representation (BREP) phantoms [3]. The organs of the human body are modeled by basic geometric blocks such as spheres, cubes, cylinders, and so on in the stylized phantom and Boolean demised. Phantom's second-generation computes the composition of small voxels organized into groups and conventions representing various organs. This second-generation of phantoms can more accurately describe the contours of objects than the first. This type of phantom has not yet been described for small structures such as skin and subcutaneous organs. The BREP phantom generation uses polygon meshes to describe the geometry. This gives it more information about geometry than the first two generations.

In dosing studies for a specific patient group, the use of computational phantoms such as ICRP (International Commission on Radiological Protection) 110/145 will not give high accuracy since they are based on aggregate data from many people and are not specific to a single patient. To be useful in computation, phantoms representing each object must be constructed rapidly and precisely. A common method is to use patient anatomical images such as CT (Computed tomography) or MRI (Magnetic Resonance Imaging). These tomographic images clearly show the organizational structure of each patient object. Each pixel value on the image is mapped to a voxel in actual three-dimensional space. The results of the computation of the dose distribution for each of these voxels or the overall dose for a group of voxels are returned after being imported into the geometry in the correct format of the various Monte Carlo algorithms. This result is assigned to each pixel in the image, and the user extracts the essential information. Various tools can convert images to geometric forms for popular simulation codes like MCNP and GEANT4. However, they still have many disadvantages that will be analyzed in more detail in the following sections. So, we developed our replacement for the old conversion process based on the Python 3 programming language and image processing techniques.

2. Content

2.1. The PHITS simulation program

PHITS (Particle and Heavy-Ion Transport Code System) is a three-dimensional Monte Carlo simulation code developed in collaboration between JAEA and many other research institutions in Europe [5]. The geometry (defined in the [Cell] block) of the PHITS program is built on a combination of Boolean operators and quadratic, cubic, and quadratic surfaces in the 3-D Cartesian coordinate system. Surfaces in PHITS are identified by a set of keywords preceded by descriptive parameters. In PHITS, faces are the basic building blocks of cells, and the cell is the element that describes the geometry of the physical system of interest. In addition, PHITS supports a feature that helps describe geometries with repeating structures called Repeated structures using the keywords *FILL*, *U*, and *LAT*. In this iterative structure, each cell is filled with a universe represented by a lattice or group of cells. For each *universe*, an identifier (ID) is assigned to the cells located in that universe via the keyword *U* [6]. Thus, if we consider each organ as a universe, and a cell element is small enough to describe the shape and material of the organs in the human body, this type of phantom voxel was published in ICRP report No. 110 and is recommended for wide use [7, 8]. At the end of 2020, a library to support writing input files for the PHITS simulation program named fitsgeo by Ivan Gordeev [8] based on the Python 3 programming language was developed. This library makes it very easy for PHITS users to describe the input file of a PHITS program. This is the fundamental foundation for to us develop software to convert MRI/CT images into phantom geometry for PHITS.

CT images, as are generally known, are collections of two-dimensional images called slices that include information on the internal anatomical structures of the individual. These images are made up of image elements, also known as pixels, and the value of each pixel is represented by numbers known as gray levels. The value of each of these pixels is determined by the density of the associated 3-dimensional space (voxel) in the space made up of the two dimensions of the pixel and the thickness of each slice. The idea of creating phantoms out of this collection of voxels was conceived and realized using MCNP simulation and programs like Scan2MC [9], SCMS [10], RTMCNP Preprocessor [11], or CT2MCNP [4]. The publisher has also created a program called DICOM2PHITS for PHITS [12] (recent versions of PHITS have been renamed RT2PHITS). The common feature of the above programs is to convert the gray level value of each pixel into the Hounsfield index and, based on the corresponding Hounsfield value range, determine what type of material it is, and use the iterative structure described above to assign each voxel to the corresponding universe space. Thus, this method is only suitable for CT images because only CT images can determine the Hounsfield index from the gray level value according to the linear formula [13, 14].

$$HU = a + b * GL \quad (1)$$

where HU is the Hounsfield index corresponding to the GL gray level value of each pixel; a and b are constants determined experimentally with simple phantoms.

Thus, in addition to being applied only to CT images, the above method can also be affected by different CT systems and the range of HU index thresholds for each type of material. Another thing to watch out for is that medical images are often confounded by various factors. This interference will also affect the calculation of the HU and cause the conversion to deviate from the correct value.

2.2. Conversion method

From the limitations mentioned above, this paper will propose a new process to convert CT images in many different formats into geometry in the MCNP or PHITS simulation program. This process consists of the 4 steps shown in Figure 1.

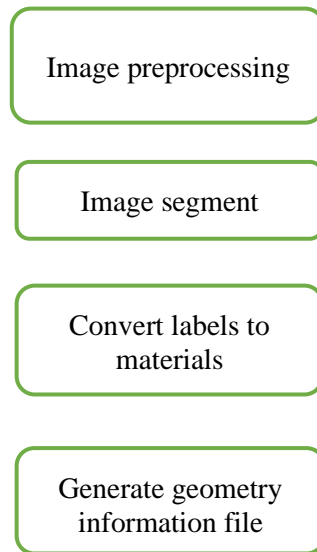


Figure 1. Process for converting DICOM images to PHITS geometry

Image preprocessing: This step is required prior to picture segmentation in order to minimize noise and improve image quality. The noise filtering method was used with spatial filtering functions such as mean, median, Gaussian, etc. Also, the size of the phantom was reduced in positions where it wasn't needed, such as the air around the head in a DICOM (Digital Imaging and Communications in Medicine) image.

Image segment: This step is the process of dividing an image into different regions of interest. Our program is integrated with the source code of the 3D Slicer application, which makes it possible for users to visualize the segmentation with the built-in toolset and many powerful features. The output result is a matrix of "labels" corresponding to each pixel in each tomographic image. Each of these labels will correspond to each of the previously segmented organ regions.

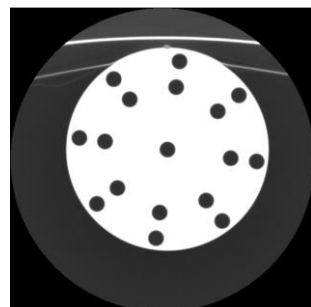
Convert labels to materials: In this step, the program will convert the label matrix into the IDs of each respective *universe* and generate files containing the corresponding material declaration information for each *universe*. These files may be used for PHITS's or MCNP's inputs.

Generate geometry information file: Once the number of universes and materials has been determined, the next step is to create the geometry. The program calculates the position and number of filled voxels for each universe and outputs a file containing the full geometry description through the fitsgeo library.

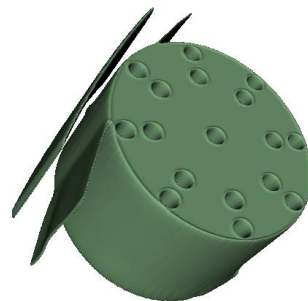
The conversion program was built in the Python language. In this study, a number of surveys were conducted to find out how accurate the suggested method was and to compare its pros and cons to existing methods.

2.3. Build some phantoms for PHITS from sets of layered images

For comparison convenience, we use a set of CT images of homogenous phantoms for medical use as an example that accompanies the RT2PHITS program. Figure 2a is a single-slice CT image of this set of images. Each image size is 512×512 pixels. The set of CT images consists of 20 slices. The spatial size of each voxel is 0.47×0.47×5 mm³. Figure 2b shows the 3D form of the phantom after segmentation using our research group's software.

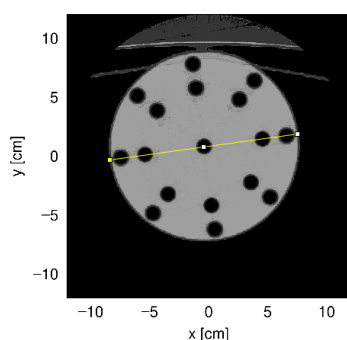


a. Image of a slice

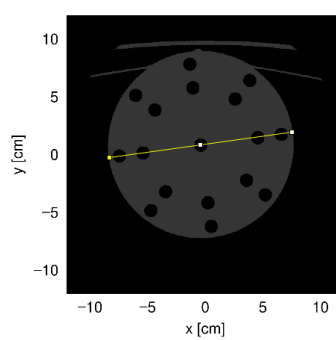


b. Segmented 3D images

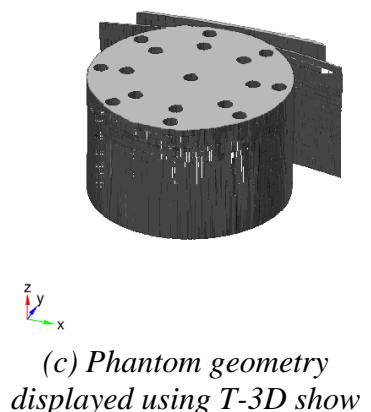
Figure 2. Medical phantom image used as a research sample



(a) Old method



(b) New method



(c) Phantom geometry displayed using T-3D show

Figure 3. 2D images shown in PHITS

Figure 3 shows a 2D PHITS image of the phantom transformed with the DICOM2PHITS conversion tool. The results show that the appearance of heterogeneous areas can be observed with the profile line. Because of the program's reliance on the Hounsfield value and the HU threshold for each substance, the conversion is not

very accurate. As in the above example, we use the threshold values of HU according to the study by Schneider [15]. If the threshold value is changed, the material part will also be changed. The conversion image with the program we created is shown in Figure 3. For ease of evaluation, we exported a slice and plotted the profile line (red line). Observing the profile line, our method gives phantoms with higher homogeneity, and holes are also more clearly represented than the conversion method from the HU coefficient.

As mentioned, some computed tomography systems do not provide information about the HU index. Therefore, using existing software to convert image data is not possible. One such CT system is the BKCT-01, currently available at the Hanoi University of Science and Technology. To test the accuracy of the convert algorithm, a phantom made of aluminum material was used, as shown in Figure 5. The BKCT-01 system was employed to obtain tomographic images of this phantom.

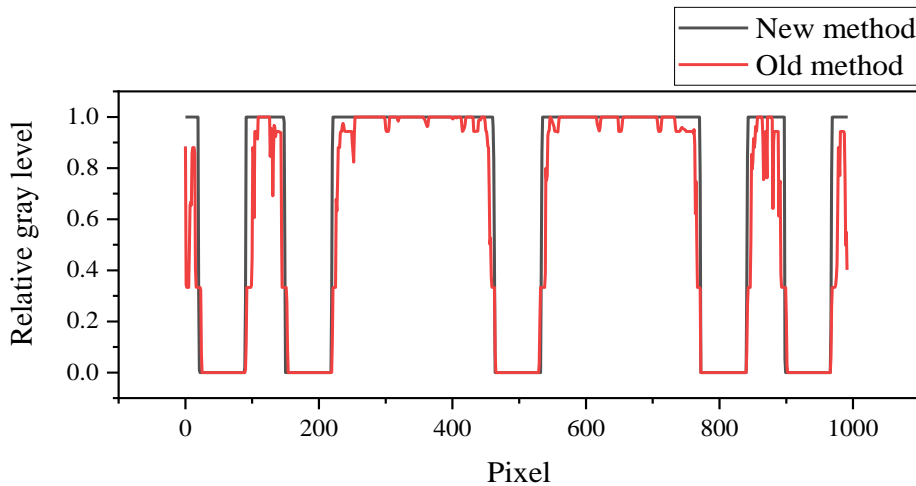


Figure 4. Compare the profile lines between the two cases above

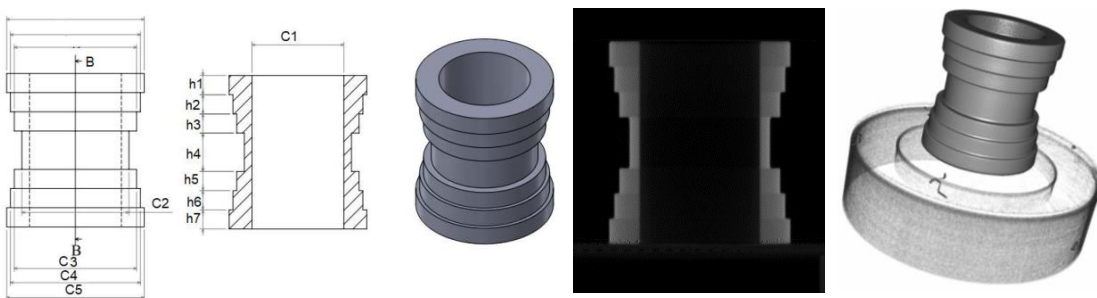


Figure 5. A high-precision aluminum phantom used to check the accuracy of the conversion program

Figure 6 shows the result shown in the PHITS program through two central slices in the Oxy and Oxz planes. This phantom is composed of 17405188 voxels with dimensions of $0.0099 \times 0.0099 \times 0.0099 \text{ cm}^3$, a volume of $16,8882 \text{ cm}^3$. We have also exported the dimensions of the edges and calculated the values of these dimensions to compare with the original design parameters to check the accuracy of the results.

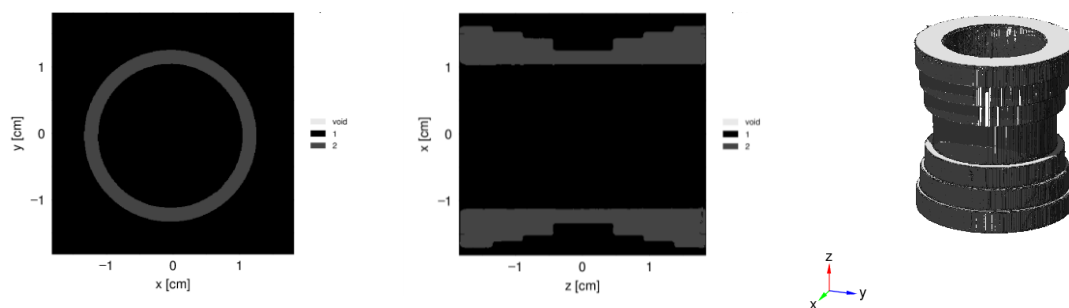


Figure 6. Results of displaying an aluminum step phantom in PHITS

Table 1 shows the size value of the phantom after being converted to geometry by the PHITS program. The sizes of the output image were measured and compared with the measured size value using a caliper with 0.02 mm accuracy and the original design value. The results show that the difference compared with the mechanical measurement method is not significant at less than 0.2%. So, it can be said that our program is accurate to a completely satisfactory level.

Table 1. Compare the dimensions of the phantom after being converted to PHITS with the design value

Dimension	Design	Caliper	PHITS	Dimension	Design	Caliper	PHITS
C1	24	23,94	23,958	h1	5	5,04	5,049
C2	28	27,96	28,017	h2	5	-	5,049
C3	32	32,02	31,977	h3	5	-	5,049
C4	34	33,98	34,056	h4	10	9,98	9,999
C5	36	35,98	36,036	h5	5	-	5,049
				h6	5	-	5,049
				h7	5	5,06	5,049

In the third case, a set of brain MRI images of a patient being treated for a brain tumor with a rotating Gamma Knife radiosurgery device were used. This set of images is 384×512×144 pixels (255×300×144 mm³). The size of the voxel is 0.5859×0.5859×0.9 mm³. We simulated a rotary radiosurgery device consisting of 30 cobalt-60 isotopic sources that were focused on the tumor with a projection field of 14 mm. The treatment time was 1113.6 seconds. The absorbed dose value is calculated using tally [T-Deposit] with the recording grid having a size and number of elements equal to the size of the set of images. In this experimental study, 14 slices (ordered from 97 to 110) were selected to minimize computation time and computer memory when running simulations. The history number was set to 10⁹ events. The results obtained from the simulation need to be corrected with a constant value (depending on the activity of 30 sources and treatment time) of 1,196×10¹¹ photons to be able to obtain results that resemble reality.

Figure 7 shows the conversion results from the original image (a), the segmented image (b), and the 2D image displayed in PHITS (c), which were segmented into regions including tumor, brain, cortex, and air region.

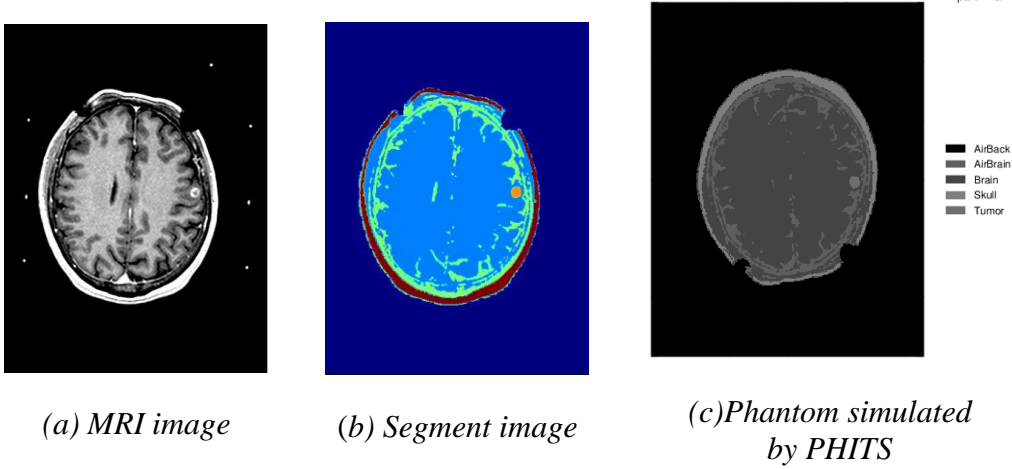


Figure 7. A human head phantom image was built from the set of MRI images

Figure 8 (a) shows the projection shot set to zero origins for convenience of calculation. When conducting phantom construction, we have shifted the position of the shot center position on the image to be placed to the original position O, which is the convergence center of 30 rotation sources. The results of the calculation of the 50% isodose curve (16 Gy) (in the red line) are shown in Figure 8(b). It is processed and mapped from grid-to-image results, and a planned 50% isodose is plotted in the yellow line. The absorbed dose on a tumor volume of 0.811 cm^3 was 30.93 Gy, which was processed by combining dose values from the voxels constituting the tumor volume. Figure 9 shows the area covered by the isodose curves from 1 Gy to 33 Gy, which were calculated using the phantom above.

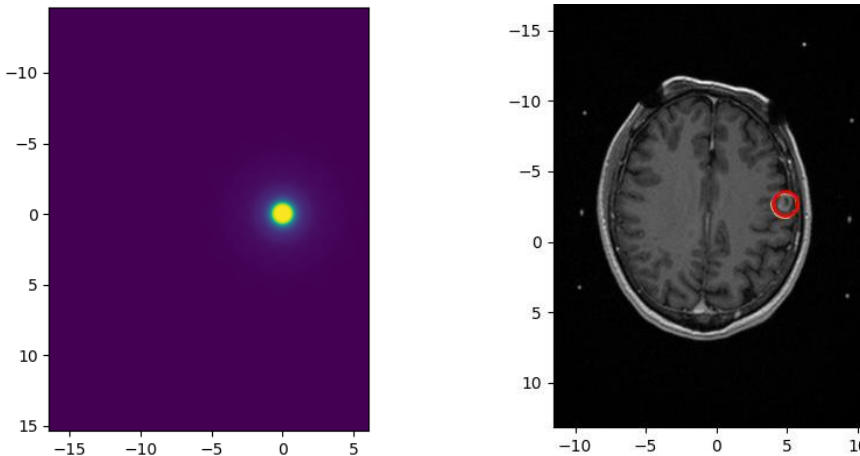


Figure 8. Calculation results are inversely mapped onto DICOM images

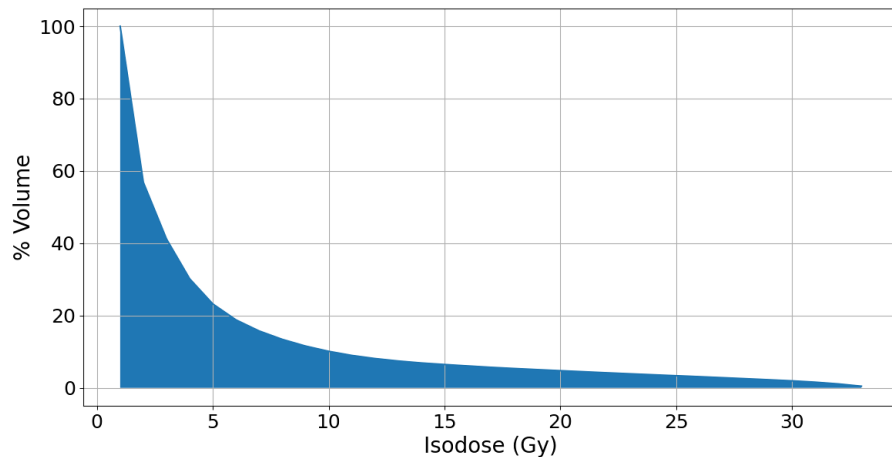


Figure 9. Relationship between absorbed dose and volume percent in the field of illumination

3. Conclusions

This study's new conversion procedure can assist users in creating input geometry for the PHITS simulation program from various types of CT images, making it more adaptable than earlier software. According to the findings of this investigation, the conversion algorithm's accuracy is higher than that of the old programs. Because the suggested conversion does not rely on the HU measure, it is suitable for a wide range of CT image data. We intend to employ artificial intelligence (AI) in the program in the near future to improve the accuracy of the image segmentation process. In other recent tests, AI was shown to be able to accurately divide and improve organs based on medical images.

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