Multistep Lattice-Voxel method utilizing lattice function for Monte-Carlo treatment planning with pixel based voxel model

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Abstract

Treatment planning for boron neutron capture therapy generally utilizes Monte-Carlo methods for calculation of the dose distribution. The new treatment planning system JCDS-FX employs the multi-purpose Monte-Carlo code PHITS to calculate the dose distribution. JCDS-FX allows to build a precise voxel model consisting of pixel based voxel cells in the scale of 0.4x0.4x2.0mm^3 voxel in order to perform high-accuracy dose estimation, e.g. for the purpose of calculating the dose distribution in a human body. However, the miniaturization of the voxel size increases calculation time considerably. The aim of this study is to investigate sophisticated modeling methods which can perform Monte-Carlo calculations for human geometry efficiently. Thus, we devised a new voxel modeling method "Multistep lattice-voxel method" which can configure a voxel model that combines different voxel sizes by utilizing the lattice function over and over. To verify the performance of the calculation with the modeling method, several calculations for human geometry were carried out. The results demonstrated that the Multistep lattice-voxel method enabled the precise voxel model to reduce calculation time substantially while keeping the high-accuracy dose estimation.

Keywords: Treatment planning, Mont-Carlo, Voxel model, Computational Dosimetry, Neutron Capture Therapy

1. Introduction

In treatment planning for boron neutron capture therapy (BNCT), Monte-Carlo method for the dose calculation is being generally applied in order to determined accurately the dose generated by the reaction between neutrons and several other elements. Japan Atomic Energy Agency (JAEA) developed a Monte-Carlo treatment planning system for BNCT, JCDS (Kumada et al., 2007). JCDS had applied MCNP to Monte-Carlo calculation code. MCNP is a general purpose Monte-Carlo N-particle transport code (Briesmeister, 2000). JCDS is being applied to BNCT clinical trials performed at JRR-4. Currently a new treatment planning system,

JCDS-FX is being developed based on the technologies of JCDS by JAEA and University of Tsukuba (Kumada et al., 2009). For Monte-Carlo calculation, JCDS-FX has employed PHITS as a multi-purpose particle Monte-Carlo transport code (Iwase, 2002). And the concept of voxel modeling method which can construct a calculation model for complicated human body has been inherited to JCDS-FX. However, the modeling method installed to the JCDS-FX has been further improved; JCDS-FX can make a precise voxel model consisting of pixel based voxel cells of the scale of 0.4x0.4x2.0mm^3 voxels in order to perform high-accuracy dose estimation. The precise voxel model is particularly effective in dose estimation at around the boundary region between air and several organs. However, the miniaturization of the voxel cell size causes calculation time to increase, the number of the voxel cells constructing the geometry correlates with the efficiency of the particles transport. Therefore, at present, it is difficult to apply the dose calculation by the pixel based voxel model to the treatment planning of BNCT. The aim of this study is to investigate sophisticated modeling method which can perform Monte-Carlo calculations for human geometry efficiently. Thus, we devised a new voxel modeling method "Multistep Lattice-Voxel Method" which can configure a voxel model that combines different voxel sizes by utilizing the lattice function over and over. To verify the performance of the modeling method, several calculations with human geometry specifications were carried out.

2. Materials and Methods

2.1 Voxel calculation model with lattice function

To perform particle transport calculations with as complicated geometry as a human body, both JCDS and JCDS-FX create a voxel calculation model based on DICOM images. JCDS configures a voxel model consisting of 5x5x5 mm^3 or 2x2x2 mm^3 voxel cells in order to perform the transport calculation efficiently. On the other hand, JCDS-FX allows to create a minute voxel model consisting of pixel based voxel cells in addition to the conventional 2x2x2mm^3 voxels, as described above. Both of the systems utilize a "Lattice" function as a means to define the voxel model easily. The lattice function is installed to MCNP as well as PHITS.

In conventional voxel models like a 5x5x5 mm^3 voxel cell model, materials for individual voxel cells are defined based on the proportion of several tissues such as bone, soft tissue, and air, rounded off to the nearest 10% fraction by volume. Thus in the boundary region, mixed materials are applied to voxel cells of a specific region. For the pixel based voxel model created by JCDS-FX, every voxel cell is defined by non-mixed materials. For that reason, the application of the pixel based voxel model results in an improvement of the accuracy of the dose estimation, especially for boundary regions.

2.2 Multistep Lattice Voxel method

In case of the pixel based voxel model with the conventional method using lattice function, the number of the voxel cells is 262,144 (512x512) per slice. In contrast, by using the Multistep Lattice-Voxel method (MLV method), the number of the voxel cells can be reduced dramatically, while keeping the accuracy of the calculation geometry. Figure 1 shows a schema of the

configuration of the voxel model with the MLV method. The MLV method configures a voxel calculation model by the following procedure; first, a CT slice (512x512pixel) is separated into 32x32 (1,024) regions, and each separated region consisting of 16x16 (256) pixels are grouped into a “large voxel region”. When the material in a large voxel region is uniform, the region is replaced with a “Single Large Voxel” cell. On the other hand, if two or more materials are mixed in the region, a “Mixed Large Voxel” cell consisting of 256 miniature voxel cells is configured using the lattice function. The size of a miniature voxel that forms the mixed large voxel is of the same size as the pixel. Accordance to the procedure, each of the large voxel regions of a single slice is converted into the “Single Large Voxel cell” or the “Mixed Large Voxel cell”, and then uneven voxel model of a slice that combines different voxel sizes are made. This modeling procedure is applied to every slice, and then every slice consisting of the uneven voxel models is put in using the lattice function again. Finally, a three-dimensional voxel model is created. The number of voxel cells of the uneven voxel model reduces substantially compared with the pixel based voxel model. Meanwhile, the material composition of the uneven voxel model is exactly the same as the pixel based voxel model.

2.3 Verification of the MLV method

To verify characteristics and performance of the MLV method, Monte-Carlo calculations making use of several different calculation models for a human geometry were performed. In the verification, a series of CT slices of a head was prepared. For the CT data, the number of the slices was 60, and the number of the pixels for a slice was 262,144 (512x512). The slice thickness was 3mm, and the pixel size was 0.5 mm. A three-dimensional head model was created from the CT data by using JCDS-FX, and then three voxel calculation models, as described as below, were configured from the 3D head model.

(a) Pixel based voxel model: all pixels were converted into miniature voxel cells directly. The number of all voxel cells was 15,728,640 (512x512 pixels x 60 Slices). Figure 2-(a) and (b) show arbitrary axial cross sections of the voxel model.

(b) Uneven voxel model: by using the MLV method, the pixel based model was converted into a voxel model mixing different voxels sizes.

(c) Material mixed voxel model: the model was created by using conventional voxel modeling method, being applied in BNCT treatment planning at present. This model was also made by using JCDS-FX. The size of each voxel cell was set as 2x2x2 mm^3. For the material definition for each voxel cell, mixed composition was set, if two or more materials were mixed in an $8mm^3$ voxel cell.

In the verification, whole region of the head for three voxel models was divided into four materials, normal tissue, bone, tumor and air, respectively.

For each calculation model, several doses and neutron fluxes, required for the BNCT treatment planning, were determined. For the transport calculations for the three models, PHITS was applied, the PHITS calculation was done by using conventional PC-Workstation (Intel Xeon Quad Core 2.4GHz, RAM:16GB, single core calculation).

To standardize the tally condition, distributions for the neutron fluxes as well as the dose rates were determined by “Mesh Tally”. First, to compare the calculation speed with regard to

the difference of the voxel segmentation, the region of the mesh tally was defined to determine the distributions in an entire field of the head, and then a mesh size was fixed as 5x5x5 mm^3. This mesh size corresponded to the typical size in the current treatment planning of BNCT. In case of the tally condition being set to 125mm^3, calculation accuracy might go down at the boundary region because estimation fields with the 125mm^3 tally straddle the different material regions. Thus, to estimate the calculation accuracy of the uneven voxel model, each model's mesh tally size was set to pixel size (0.5x0.5x3mm^3) so that each estimation field corresponds to the material regional division. Finally values for doses and fluxes were also determined for each mesh region.

3. Results and discussions

Figures 3-(a) and (b) show axial cross section views at around tumor region shown in the Figure 2-(a) for both of the minute voxel models. Fig.3-(a) shows the voxel model build by using the pixel based voxel method, and Fig3-(b) shows the uneven voxel model with the MLV method for the same area. The figure of the uneven model demonstrates that many of the large voxel regions for "tumor" and "brain" were converted into the single large voxels by the MLV method. And the figure also shows that the other large voxel regions which included two or more materials were converted into the mixed large voxel cell. For the uneven voxel model, the number of the voxel cells constituting the slice shown in Fig.2-(a) is approximately 66,000, though the number of the voxel cells for the pixel based voxel model was 262,144 (512x512). For the slice, the number of the voxel cells has fallen by nearly 75% as compared to the pixel based model. While the number of the voxel cells of the slice for the uneven model is approximately 77,800. The number is larger than the voxel number of the former slice. The reason comes from the fact that the shape of skull region of the latter axial cross section is more complex than the former axial cross section.

Next, the results of the dose calculations gained with each model were compared. The statistical uncertainties of the calculated values around the tumor region were below 3% for each model. The calculated values for neutron fluxes and each dose rate determined from the uneven voxel model were in good agreement with the values of the pixel based voxel model, within each statistical error. It stands to reason that values of the uneven model correspond to the pixel based model's one because the geometry (material configuration for each miniature voxel cell) configured by the MLV method is equal to the geometry of the pixel based model.

For estimations of the calculation time, in the estimation using the 125mm^3 mesh tally, the calculation for the pixel based voxel model has taken as about 5.2 hours per 10 million NPS. In contrast, the calculation time for the uneven voxel model was approximately 2.5 hours per 10million. So, by using the uneven voxel model, the calculation time was shortened about 50% against the pixel based voxel model. The results proved that the MLV method enabled the precise voxel model to reduce calculation time substantially while keeping the high-accuracy dose estimation. By comparison, calculation time for the material mixed voxel model was about 1.4 hours per 10 million NPS, which means, computing time was nearly cut in half as compared to the uneven model's calculation time. For the material mixed voxel model, the number of the voxel cells per slice was about 33,800, less than half the number of the voxel cells of the uneven model. However, for the material mixed voxel model, there is a possibility that the calculation

results involve characteristic discrepancies caused by the application of mixed composition to the voxels at boundary region. In particular, a large calculation error occurs at boundary region between air and head.

For the estimation of the calculation accuracy with the pixel based meth tally, the calculated values of the uneven voxel model were matched the values of the pixel based voxel model. However the calculation results from the material mixed voxel model were approximately 5% to 18% higher than the results of both of the detailed voxel models at the boundary region between air and skin.

At present, we are improving the modeling algorithm further to increase efficiency of the particle transport calculation. For example, in the building process of the single large voxel, the region of the single large voxel expands to 16x16x2slices (512pixels). By this means, the number of voxel cells of the model will reduce further, the particle transport of the Monte-Carlo calculation is expected to become more efficient.

4. Conclusions

In order to make particle transport in the Monte-Carlo calculation more efficient, the Multistep Lattice-Voxel method, which can make a voxel model that combines different voxel sizes by utilizing the lattice function over and over, was devised. The verification results proved that the method enables the precise voxel model to reduce calculation time substantially while keeping the high-accuracy dose estimation. As a result, the modeling method has been installed to JCDS-FX, with several more verification test are being performed at present. Furthermore, we are still carrying out sophistication of the modeling method to work toward practical use of the new treatment planning system with more precise computational dosimetry.

Acknowledgments

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Figures

Figure 1 : Algorithm of the Multistep Lattice Voxel method.

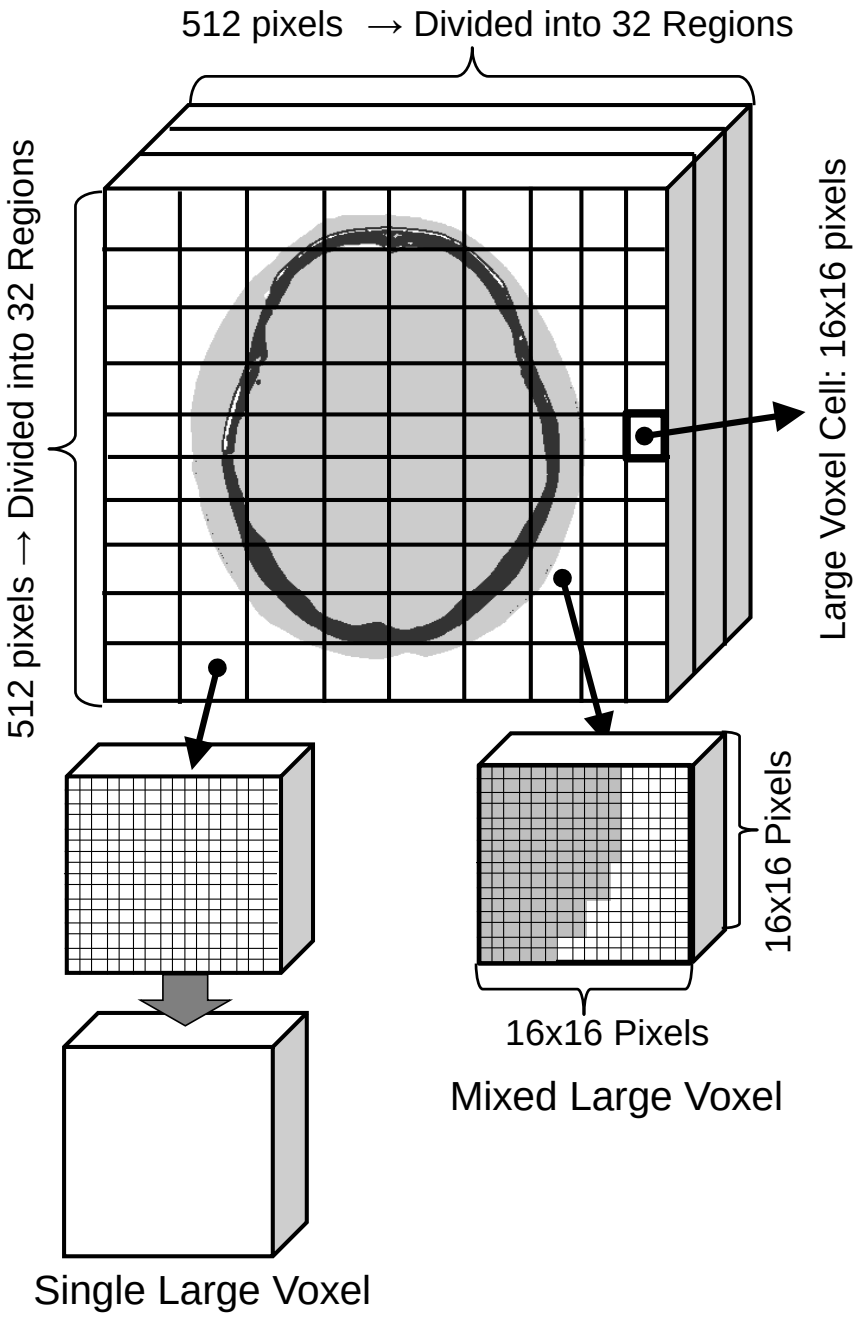

Figure 2: Slices in the three-dimensional head model.

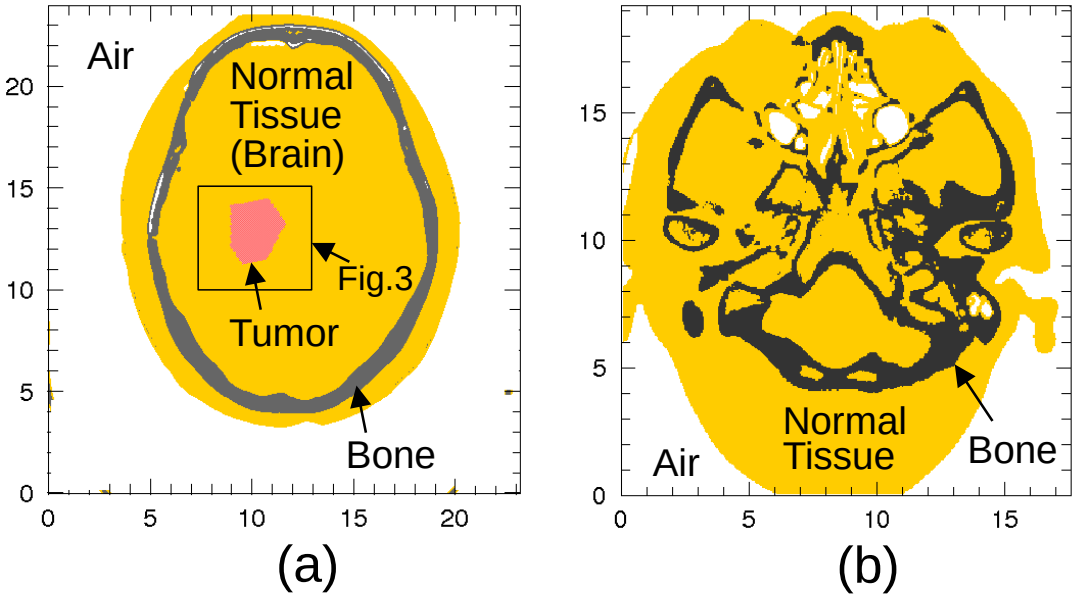

Figure 3: Cross section views for (a) pixel based voxel model and (b) uneven voxel model with the MLV method.