Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

GPU-based prompt gamma ray imaging from boron neutron capture therapy

Do-Kun Yoon, Joo-Young Jung, Tae Suk Suh*
Department of Biomedical Engineering and Research Institute of Biomedical Engineering, College of Medicine, Catholic University of Korea, Seoul 505, Korea

1. Introduction

Boron neutron capture therapy (BNCT) is a radiation therapy method using the $^{10}B(n, \alpha)^{7}Li$ reaction. Through reaction between the thermal neutron (< 1 eV) and ^{10}B (boron), an alpha particle and a ^{7}Li (lithium) ion are emitted from the neutron capture point. This reaction can be applied to the therapy and diagnosis about the tumor simultaneously. After the compound labeled with the boron is accumulated at the tumor site, the alpha particle induced by the reaction between the thermal neutron and the boron induces tumor cell death. Also, the 478 keV prompt gamma ray is emitted from the same reaction point [1]. If this single prompt photon is detected by single photon emission computed tomography (SPECT), the tomographic image of the therapy region can be monitored during the radiation treatment [2].

However, in order to confirm the therapy region using the image during the treatment, the image needs to be provided promptly. Due to a relatively long acquisition time required to get SPECT images, both reduced number of projections and the fast image reconstruction schemes are needed to provide the images during radiation treatment. Thus, the purpose of this study is to realize the fast reconstruction of the prompt gamma ray image from BNCT using graphics processing unit (GPU) while improving image quality with fewer number of projections. In this study, the therapeutic environment of BNCT was simulated by using the Monte Carlo n-particle extended (MCNPX, Ver. 2.6.0, Los Alamos National Laboratory) simulation tool. In our previous study, it was to provide correctness of image reconstruction of prompt gamma image using many projections. However, the scope of the current study is the fast reconstruction of the image with a few projections for realistic usage of the BNCT as a tumor volume confirmation during radiation treatment.

2. Methods and Results

In the simulation, the neutron generator for the BNCT, the four heads SPECT modality and phantom were simulated using the Monte Carlo simulation tool. Especially, in order to apply this research result to the clinical field, the geometry of the BNCT facility was adopted from a research paper that details the design of such a BNCT facility.

The emission of the thermal neutrons (< 1 eV) from the neutron generator in the simulation was directed toward the phantom. The spherical water phantom (diameter = 18 cm, density = 1 g/cm^3) was comprised of four boron uptake regions (BURs). These BURs (density =2.08 g/cm^3) were a spherical pattern of different sizes and locations (diameter = 5, 4, 3, and 2 cm; coordinates = (5, 0, 0), (0, 0, 5), (-5, 0, 0), and (0, 0, -5)) [3]. When the thermal neutrons from the neutron generator react with the boron in the BURs, the 478 keV prompt gamma rays are detected by the SPECT scanner comprising the detector and the collimator. The detector material was chosen as the lutetium yttrium oxyorthosilicate (LYSO, density = 7.3 g/cm^3) which is currently available as the detector material for nuclear imaging such as SPECT and PET [4]. The detector size was defined as the 28 cm × 28 cm × 3 cm. And the array of the parallel lead collimator (density = 11.3 g/cm^3) was 70 × 70 with the 2 mm thickness and 20 cm height [5]. In order to get a prompt gamma ray image during radiation treatment, the total neutron flux was set as the 1.28×10^{10} n/cm^2•sec, which is a quarter of the actual neutron flux for the BNCT. To reduce the data acquisition time, only 16 projections and 32 projections during the emission of the limited flux were acquired. The reconstruction of tomographic image was performed with the different two modes. The first reconstruction mode was conventional ordered subset expectation maximization (OSEM) using the central processing unit (CPU; Intel(R) Core i7 (3.40 GHz) CPU with the 12.0 GB RAM), another reconstruction mode was a modified OSEM using the GPU.

Basically, the system matrix was stored at the memory by the reconstruction process using CPU. In case of the reconstruction using the GPU, the NVIDIA GeForce GTX 770 with the 2 GB memory GDDR5 graphic card and the compute unified device architecture (CUDA) inserted at the MATLAB (R2012a, Mathworks Inc., MI, USA) codes were used to reconstruct the image [6]. In order to achieve the maximum efficiency of the parallel computing on the GPU system, the divided computation between 1024 threads were distributed without any overlap. The space of the image was divided as the 32 × 32 (1024 domains) to the block. Hence, the conventional OSEM was modified to perform the iteration at each individual area without the overlap. The matrix number of the reconstructed image was the 96 × 96 with a 30 cm × 30 cm field of view (FOV). The rotation angles of the 16 and 32 projections were 22.5° and 11.25°, respectively. The setting of the OSEM for the reconstruction about all the images was 8 subsets and 15 iterations.

After the reconstruction of the tomographic image, the analysis of the geometric accuracy was performed using the receiver operating characteristic (ROC) curve. The reconstructed image using the GPU was overlapped with the original pattern image of the phantom by using the pixel address matching method. In the area of the four BURs, a true positive signal was collected by the signal intensity with the tolerance values (0-10%), and a false negative signal was collected from the region outside the BURs. The area under the ROC curves (AUCs) was calculated from the ROC curve of the four BURs.

Figure 1 shows the energy spectrum of the prompt gamma ray obtained by the detector. The prompt gamma ray peak of the 478 keV (relative error: 0.26%) appeared on the spectrum with a full width at half maximum (FWHM) of 41 keV (energy resolution = 6.4%). To reconstruct the tomographic image, the effective events about the 478 keV photons were sorted by using energy window as the FWHM.

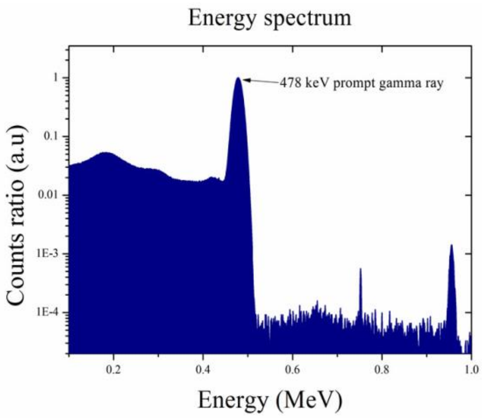

Fig. 1. Energy spectrum including the 478 keV prompt gamma ray peak in the Monte Carlo simulation. The 478 keV prompt gamma ray events were used to reconstruct the tomographic image from the boron neutron capture therapy (BNCT).

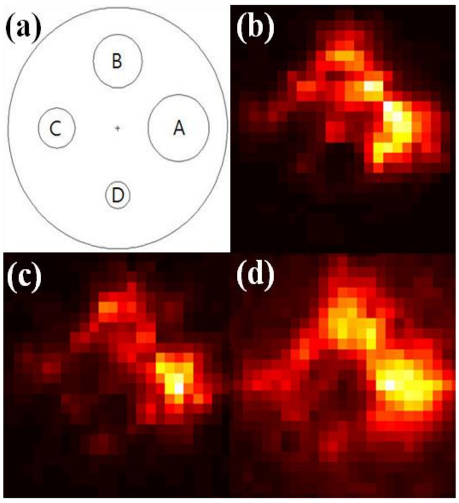

Fig. 2. Original pattern of the phantom including four boron uptake regions (BURs) (a), the reconstructed tomographic image of the prompt gamma ray from the central processing unit (CPU) computation with 16 projections (b), the reconstructed tomographic image of the prompt gamma ray from the CPU computation with 32 projections (c), the reconstructed tomographic image of the prompt gamma ray using the graphics processing unit (GPU) computation with 16 projections.

Figure 2 shows the reconstructed tomographic images using the CPU and GPU. Figure 2(a) shows the pattern of the spheres placed in the phantom used in the simulation. Each of the four spheres A, B, C, and D is 5, 4, 3, and 2 cm in diameter, respectively, and they are the BURs for the reaction with neutron. The image of the pattern using the prompt gamma ray events of BURs was reconstructed. Figures in (b) and (c) in Fig. 2 show the reconstructed tomographic images with the 16 and 32 projections, respectively, using the conventional OSEM reconstruction algorithm based on CPU computation. The D-region was hard to be confirmed from the reconstructed image with 16 projections in Fig. 2(b). However, the reconstructed tomographic image with 32 projections shows the D-region faintly in Fig. 2(c). Because the acquisition time of 32 projections (approximately 18 minutes) is almost same with the BNCT time (approximately 20 minutes), in order to prevent to be discrepant to the purpose of the research, the comparison about only 16 projections was performed. The reconstructed image with 32 projections using the CPU computation was inserted for the visible comparison of the image quality with the reconstructed image using the GPU. The image in Fig. 2(d) is the reconstructed tomographic image with 16 projections using the modified OSEM based on the GPU computation. Although only 16 projections were used to reconstruct the image, the reconstructed image using the GPU clearly shows the D-region. Because the GPU computation was performed individually according to the thread, although the signal intensity was stronger than the reconstructed image using conventional OSEM from the CPU, the basic noise level (GPU: 8.1% (average), CPU: 2.6% (average)) also more strong with the same conditions of the reconstruction. In order to compare the performance of the two reconstruction methods, the computation time of each reconstruction was measured, and it was reported in Table 1.

Table I: Comparison of the measured image reconstruction time between the central processing unit (CPU) and graphics processing unit (GPU).

Reconstruction time (ms) / Iteration number (8 subsets)	CPU 16 projections	CPU 32 projections	GPU 16 projections	Ratio (16 projections)
1st	8,965	17,923	237	× 37.8
15th	382,901	1,047,533	1,956	× 195.8

The unit of the computation time was set as the ms. For reconstruction of the images from 16 projections, the computation time at first iteration and at 15th iterations using 8 subsets for both were listed. The reconstruction time for the first iteration using CPU was approximately 9 seconds while it was 237 milliseconds using the GPU, which is 38 times faster than using CPU. Also, the 15 iterations reconstruction time from the CPU were required as approximately 6 minutes. On the other hand the speed of the 15 iterations reconstruction time using the GPU was about 2 seconds, which is 196 times faster than CPU computation. Basically, the increase of the iteration causes the long reconstruction time. When the GPU computation is used to reconstruct the image with the iterations, the increase of the number of iteration induces more efficient computation time. However, the efficiency of the GPU computation depends on the efficient distribution of the parallel computation to the threads. Therefore, presence of better effective GPU management scheme, there is potential that the computational efficiency can be greatly improved.

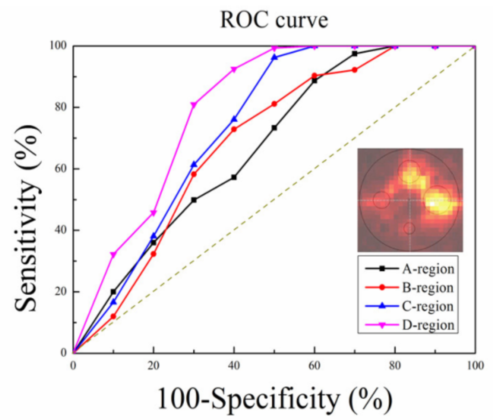

Fig. 3. Receiver operating characteristic (ROC) curve for the reconstructed tomographic image of the prompt gamma ray using the graphics processing unit (GPU) computation with 16 projections. The area under ROC curve (AUC) values of the four boron uptake regions (BURs) were calculated to be 0.6726 (A-region), 0.6890 (B-region), 0.7384 (C-region), and 0.8009 (D-region), respectively.

Figure 3 shows the ROC curve of the four BURs. The four AUC values were 0.6726 (A-region), 0.6890 (B-region), 0.7384 (C-region), and 0.8009 (D-region), respectively. From the results of the ROC curve analysis, the size of the BUR becomes smaller, the larger the AUC was calculated. In comparison with our preceding research, the relatively accurate reconstructed image was acquired using the GPU computation with fewer projections in this study. Also, greatly fast reconstruction of the prompt gamma ray image during BNCT was achieved.

3. Conclusions

In this study, the tomographic image based on the prompt gamma ray from the SPECT was acquired and reconstructed using the GPU computation in order to realize the fast reconstruction of the prompt gamma ray during BNCT. For the acquisition of the projection data, the BNCT facility and SPECT system were simulated using the Monte Carlo simulation tool. The computation time for image reconstruction using the GPU with the modified OSEM algorithm was measured and compared with the computation time using CPU. Through the results, we confirmed the feasibility of the image reconstruction for prompt gamma ray image using GPU for the BNCT. In the further study, the development of the algorithm for faster reconstruction of the prompt gamma ray image during the BNCT using the GPU computation will be conducted. Also, the analysis of the target to background level about the reconstructed image will be performed using the extracted image profile.

REFERENCES

[1] V. Nievaart, D. Légràdy, R. Moss, J. Kloosterman, T. van der Hagen, and H. van Dam, Application of adjoint Monte Carlo to accelerate simulations of mono-directional beams in treatment planning for Boron Neutron Capture Therapy, Medical Physics, Vol. 34, p. 1321, 2007.

[2] P. Munck af Rosenschöld, W. Verbakel, C. Ceberg, F. Stecher-Rasmussen, and B. Persson, Toward clinical application of prompt gamma spectroscopy for in vivo monitoring of boron uptake in boron neutron capture therapy, Medical Physics, Vol. 28, p. 787, 2001.

[3] D. Rej, M. Pickrell, and D. Wrobleski, Neutron-capture-induced radiation treatment of polymeric materials, Applied Physics Letters, Vol. 68, p. 2517, 1996.

[4] E. Testa, M. Bajard, M. Chevallier, D. Dauvergne, F. Le Foulher, N. Freud, J. Létang, J. Poizat, C. Ray, and M. Testa, Monitoring the Bragg peak location of 73 MeV/u carbon ions by means of prompt γ-ray measurements, Applied Physics Letters, Vol. 93, p. 093506, 2008.

[5] I. Murata, T. Mukai, S. Nakamura, H. Miyamaru, and I. Kato, Development of a thick CdTe detector for BNCT-SPECT, Applied Radiation and Isotopes, Vol. 69, p. 1706, 2011.

[6] D.-K. Yoon, J.-Y. Jung, K. Hong, and T. Suh, Tomographic image of prompt gamma ray from boron neutron capture therapy: A Monte Carlo simulation study, Applied Physics Letters, Vol. 104, p. 083521, 2014.