Calculation of the characteristics of clinical high-energy photon beams with EGS5-MPI

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Abstract
A graphite calorimeter has been developed as a Japanese primary standard of absorbed dose to water in the high-energy photon beams from a clinical linac. To obtain conversion factors for the graphite calorimeter, the beam characteristics of the high-energy photon beams from the clinical linac at National Metrology Institute of Japan were calculated with the EGS5 Monte Carlo simulation code. To run the EGS5 code on High Performance Computing machines that have more than 1000 CPU cores, we developed the EGS5 parallelisation package “EGS5-MPI” by implementing a message-passing interface. We calculated the photon energy spectra, which are in good agreement with those previously calculated by D. Sheikh-Bagheri and D. W. O. Rogers (Med. Phys. 29 3). We also estimated the percentage-depth-dose distributions of photon beams from the linac using the calculated photon energy spectra. These calculated percentage-depth-dose distributions were compared with our measured distributions and were found they are in good agreement as well. We will calculate conversion factors for the graphite calorimeter using our results.

1. Introduction
The Japanese primary absorbed dose standard in $^{60}$Co-$\gamma$ ray field was established in 2011 by using a graphite calorimeter. As the next step in the absorbed dose standard development, the National Metrology Institute of Japan (NMIJ) has been developing the absorbed dose standard in high-energy photon beams from a clinical linac using a graphite calorimeter. The calorimetric method using a graphite calorimeter requires a conversion factor from the dose to graphite to the dose to water. Further, evaluation of the characteristics of photon beams plays an important role in the determination of the conversion factor [1].

The characteristics of the high-energy photon and electron beams from a clinical linac are important for estimating the various correction factors of clinical radiation dosimetry. The beam characteristics have been estimated experimentally and numerically [2–4]. Kawrakow et al., Rogers et al., and Hirayama et al. developed Monte Carlo (MC) calculation codes [5–7]. These codes can be used for calculating the characteristics or the dose distribution of the high-energy photon and electron beams from a clinical linac. In particular, the BEAM code developed by Rogers et al. is a very suitable MC code for calculating photon beams from a clinical linac [6]. BEAM codes are widely used for the dosimetry on the radiation therapy using a clinical linac. However, these calculation codes do not support the message-passing interface (MPI) or any other parallel calculation techniques. Further, it is very difficult to run BEAM codes on a cluster machine, which has many nodes and CPU cores, because users have to manually manage the random seed number and other parameters of each calculation process.

In this work, we have developed the “EGS5-MPI,” which is the extended package of the MC calculation code Electron Gamma Shower version 5 (EGS5), for parallel calculation using MPI. To obtain the conversion factor of a graphite calorimeter, we calculated the characteristics of the high-energy photon beams from the
clinical linac at NMJJ. We then compared the percentage-depth-dose (PDD) distributions estimated experimentally and numerically.

2. Method

To obtain the conversion factors for the graphite calorimeter, we calculated the beam characteristics of the high-energy photon beams from the clinical linac at NMJJ. To calculate as many cases as possible to reduce statistical uncertainty, we developed the extended EGS5-MPI package for using MPI on the EGS5 MC code.

2.1. EGS5-MPI

The EGS5-MPI provides the subroutines and common variables for managing the random seed number and the MPI environment. In the EGS5-MPI calculation code, users can call the MPI subroutines. Therefore, we used the MPI subroutines for final calculation results or for changing the calculation parameters during each process. The most important function of EGS5-MPI is the random seed number management. The random seed number (inseed) of EGS5 for each MPI process is generated automatically by the root process (which has an MPI process rank number of 0) and provided through the MPI communication protocol. The root process has the main random seed number, which is only input manually by user. The EGS5-MPI calculation code can be executed on UNIX-like operating systems (Linux, Cygwin, Free-BSD, Mac OSX, etc.). In many cases, the EGS5-MPI code can be executed on a large cluster machine that has more than 1000 CPU cores.

2.2. Calculation of the beam characteristic

We calculated the beam characteristics of 6, 10, and 15 MV high-energy photon beams from the clinical linac at the NMJJ by using EGS5-MPI. We used the geometry and material data of the clinical linac from the information provided by Elekta K. K. The energy distribution and beam width of the incident electron beam at its X-ray target is also input along with the information provided by Elekta K. K. The electron cut-off energy (ECUT) is 0.7 MeV, and the range rejection (ESAVE) of the X-ray target and other linac parts are 0.7 MeV and 2.0 MeV, respectively. Other calculation parameters are listed in Table 1. The energy spectra of the photon beams were calculated on our home-made cluster machine (AMD Phenom II, 3.2 GHz, six cores, four nodes). We simulated the photon energy spectra with about $10^{10}$ incident electrons, and all information (charge, energy, position, direction) about the photons and the electrons at the detector plane (Source to Surface Distance (SSD) = 80 or 100 cm) was saved as binary data.

We also calculated the PDD with $10^{10}$ photons by using the HPC machines at the Univ. of Tokyo and Kyushu Univ., which have more than 1000 CPU cores. In the depth-dose calculation, ECUT and ESAVE were 0.521 MeV and 0.6 MeV, respectively. Other parameters were essentially the same as those of the beam-characteristics calculation. To reduce the calculation time, we assumed that the photon beam had a uniform distribution in a plane perpendicular to the photon beam direction, and the secondary electrons and scattered photons were not included in the photon beam. The calculation time of the PDD was about 5 h. The parallelisation efficiency of the PDD calculation was 99.999%. The EGS5-MPI is considered very suitable for calculation on the HPC machines. To compare the calculated and experimental results, we measured the PDD distribution of the NMJJ linac by using a 3D water phantom (Blue Phantom, IBA Inc.) and a pinpoint ionisation chamber (CC-13, Scanditronix Wellhofer).

Table 1. Calculation parameters used in EGS5 for the beam characteristics calculation

| Parameter   | Description                               |
|-------------|-------------------------------------------|
| ECUT = 0.70 | Energy cut-off for electrons (MeV)        |
| PCUT = 0.01 | Energy cut-off for photons (MeV)          |
| ESAYE (Target) = 0.70 | Range rejection on x-ray target (MeV) |
| ESAYE (Other parts) = 2.0 | Range rejection (MeV) |
| IBRDST = 1 | Koch and Motz formula for Bremsstrahlung photons |
| IPRDST = 1 | Motz, Olsen, and Koch formula for pair production |
| IPTHER = 1 | Switches for PE-angle sampling           |
| IEDGFL = 1 | K & L-edge fluorescence                   |
| IAUGER = 1 | K & L-Auger                               |
| IRAYLR = 1 | Rayleigh scattering                       |
| LPOLAR = 1 | Linearly polarised photon scattering      |
| INCOHR = 1 | S/Z rejection                             |
| IPROFR = 1 | Doppler broadening                        |
| IMPACR = 1 | Electron impact ionisation                |
3. Results and Discussion

The calculated energy spectrum of a 6 MV photon beam from the clinical linac at NMIJ is shown in Fig. 1. The x-axis represents the photon energy, and the y-axis represents the photon counts per 100 incident electrons. For comparison, the energy spectrum for an Elekta linac calculated by Sheikh-Bagheri and Rogers using the BEAM code [4] is also shown in Fig. 1. As can be seen clearly, the overall shape of the present calculated energy spectrum is in good agreement with that by Sheikh-Bagheri. This agreement suggests that our parallel MC calculation code using EGS5-MPI can provide the same results as that obtained using the BEAM code.

Figure 1. Energy spectra of 6 MV photon beams from an Elekta clinical linac. The solid line shows the present calculation result. The dashed line shows Sheikh Bagheri’s calculation result (Med. Phys. 29 3) [4]. These data show the energy spectra for the region 0 < r < 2.25 cm at the detector plane (SSD = 100 cm).

We have calculated the PDD distributions of photon beams. The calculated and experimental PDD distributions of the 15 MV photon beam are shown in Fig. 2. The x-axis represents the water depth, and the y-axis represents the normalised dose. The differences at each depth point are also shown in Fig. 2. As can be seen, the experimental PDD distribution agrees well with the calculated one. This result strongly supports the validity of our calculation method. However, there are small systematic differences near the depth of the maximum dose. These differences arise from the electrons emitted from the linac head [4]. The contribution of the secondary electrons on the surface dose distribution is only a few percent of the photon beam contribution, and the range of the secondary electrons in water is 3–5 cm.

To take the secondary electrons into account, we have calculated PDD distributions more precisely with the binary data of photon beams, which include the data of all particles (secondary electrons and scattered photons, etc.) from the linac head. The precise calculations are also shown as the open symbols in Fig. 2. As can be seen, the systematic differences between the calculated and the experimental PDD distributions disappeared. However, the statistical uncertainty increased because the number of calculation events in the binary data is smaller than $10^9$ cases due to the calculation time.
Figure 2. Percentage depth dose (PDD) distribution of a 15 MV photon beam (SSD = 90 cm). The dotted line shows the experimental distribution. The solid line shows the calculated result. The differences between the experimental and calculated distributions are shown in top-right inset. The filled circles show the differences for the PDD distribution calculated using the energy spectrum of the photon beam. The open circles show the differences for the PDD distribution using the binary data of the photon beam, which include the secondary electrons and scattered photons.

4. Conclusion
The beam characteristics of high-energy photon beams from the clinical linac at NMIJ have been calculated with EGS5-MPI. The calculated photon energy spectra are in good agreement with the previous ones by Sheikh-Bagheri and Rogers [4]. For comparison with the experimental results, we also calculated the percentage depth dose distribution using the energy spectra of photon beams. These calculated PDD distributions also agree with the experimental ones. EGS5-MPI is a very powerful tool for EGS5 parallelization on the HPC machine. EGS5 users can develop the parallel MC calculation on their desktop PCs and execute it on the HPC machines. In future works, we will calculate the conversion factors for our graphite calorimeter using our present energy spectra results. The new primary absorbed dose standard for high-energy photons from a clinical linac is going to be established in 2013.

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