Benchmark Results of a Monte Carlo Treatment Planning system

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Recent advances in radiation transport algorithms, computer hardware performance, and parallel computing make the clinical use of Monte Carlo based dose calculations possible. To compare the speed and accuracies of dose calculations between different developed codes, a benchmark tests were proposed at the XIIth ICCR (International Conference on the use of Computers in RadiationTherapy, Heidelberg, Germany 2000). A Monte Carlo treatment planning comprised of 28 various Intel Pentium CPUs was implemented for routine clinical use. The purpose of this study was to evaluate the performance of our system using the above benchmark tests. The benchmark procedures are comprised of three parts. a) speed of photon beams dose calculation inside a given phantom of 30.5 cm×39.5 cm×30 cm deep and filled with 5 mm^3 voxels within 2% statistical uncertainty. b) speed of electron beams dose calculation inside the same phantom as that of the photon beams. c) accuracy of photon and electron beam calculation inside heterogeneous slab phantom compared with the reference results of EGS4/PRESTA calculation. As results of the speed benchmark tests, it took 5.5 minutes to achieve less than 2% statistical uncertainty for 18 MV photon beams. Though the net calculation for electron beams was an order of faster than the photon beam, the overall calculation time was similar to that of photon beam case due to the overhead time to maintain parallel processing. Since our Monte Carlo code is EGSnrc, which is an improved version of EGS4, the accuracy tests of our system showed, as expected, very good agreement with the reference data. In conclusion, our Monte Carlo treatment planning system shows clinically meaningful results. Though other more efficient codes are developed such like MCDOSE and VMC++, BEAMnrc based on EGSnrc code system may be used for routine clinical Monte Carlo treatment planning in conjunction with clustering technique.

Keywords : Monte Carlo, Radiotherapy treatment planning, Benchmark

INTRODUCTION

The use of Monte Carlo techniques for routine clinical treatment planning will soon be possible in the sense that various commercial producers of treatment planning systems are actively developing such systems. Since it has long been thought that Monte Carlo techniques represent the "ultimate" answer to the problem of accurate dose calculation, the commercialization of these techniques would appear to be highly desirable.

However there are many tricky ways to reduce the calculation time in the development of routine clinical Monte Carlo techniques. The speed of the calculations is still an issue since if they take too long, Monte Carlo will never be used routinely in the clinic. A second issue concerns the accuracy of the calculations when actually implemented in a commercial system.

To compare the speed and accuracies of dose calculations between different developed codes, a

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benchmark tests[1] were proposed at the XIIIth ICCR (International Conference on the use of Computers in Radiation Therapy, Heidelberg, Germany, 2000). The benchmark results of several codes were reported.[2-4]

A Monte Carlo treatment planning comprised of 28 various Intel Pentium CPUs was implemented in our department for routine clinical use. The purpose of this study was to evaluate the performance of our system with the same benchmark test.

MATERIAL AND METHODS

1. System overview

A Linux cluster computing system consisting of 8 Pentium-III PC with dual 650 MHz CPUs and 6 Pentium-IV with dual 1.2 GHz CPUs was installed for clinical use of Monte Carlo dose calculation. Fig. 1 shows the schematic diagram of our system. Monte Carlo dose calculation was performed using BEAMnrc code, which developed originally from BEAM code. BEAM is a Monte Carlo simulation system[5] for modelling radiotherapy treatment machines, as show by Fig. 2, which was developed as part of the OMEGA project to develop 3-D treatment planning for radiotherapy planning of electron beams. BEAMnrc is built on the EGSnrc code system[6] and must be run on a Unix-based system. All computers has 512 MB main memory and integrated with 100 Mbps network card. the Generic NQS (network queueing system)[7] was installed at each computer node for parallel processing of the Monte Carlo dose calculation.

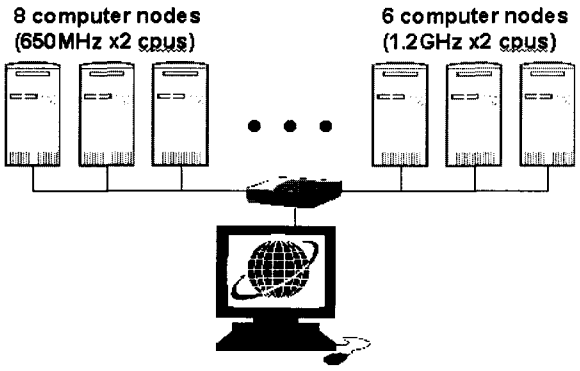

Fig. 1. Schematic diagram of a Linux cluster system installed for the purpose of routine clinical treatment planning using Monte Carlo techniques.

2. Benchmark tests

The benchmarking procedures are comprised of three parts and briefly described as bellows.

1) Speed of photon calculations

The first one is to test speed of a photon calculation. The incident beam is given to be a 6 MV spectrum from a point source at 100 cm SSD and collimated to 10×10 cm^2 at the phantom surface. The phantom is 30.5 cm$\times$39.5 cm$\times$30 cm deep and filled with 5 mm^3 voxels. The odd dimensions are to ensure a voxel on the central axis but otherwise represent a realistic size. The voxels are to be filled randomly with one of 4 materials (water, aluminium,

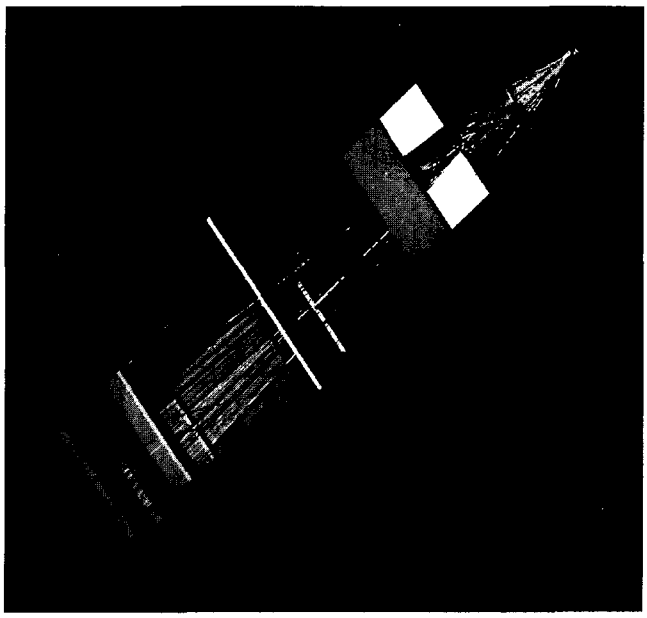

Fig. 2. Display of modelling a radiotherapy treatment machine using BEAM code. Every geometries and materials consisting of a treatment head can be accurately modeled with BEAM code system. It shows Siemens electron beam modeled by the author using EGS_WINDOW tool.

lung (ICRU, p=0.26 g/cm^3) and graphite) although if a particular algorithm's speed does not make use of voxels being the same material, then using water everywhere is acceptable.

For specification of precision to avoid issues about the uncertainty on the uncertainty, a neutral way to specify precision was proposed to sum in quadrature the estimated relative uncertainties in all voxels with a dose greater than some arbitrary lower dose limit, say $D_{max}/2$, and from this find the average relative uncertainty. For the timing comparison the precision is requested to be an average relative statistical uncertainty on these voxels of 0.02 or less. The above calculation time is to be scaled to one Intel P-III 500 MHz machine.

2) Speed of electron calculations

The second part is the same question as the first one for mono-energetic electron beams with energies of 6 MeV and 20 MeV.

3) Accuracy of calculations

The last part is to evaluate accuracy of photon and electron beam calculations. The phantoms for photon beam calculations are the same outer dimensions as in question I but they are now slab phantoms. From 0 to 3 cm is water, 3 to 5 cm is aluminium, 5 to 12 cm is lung and 12 to 30 cm is water. The voxels are 5 mm^2 in the x-y directions but only 2 mm deep to increase the resolution. The photon beam is a uniform 18MV beam from a realistic clinical accelerator as calculated at NRCC (Natiotional Research Council of Canada) using the BEAM code. The result is to be compared with EGS4/PRESTA and these are also available on-line.[8] The statistical precision of this reference calculation is ±0.3%.

For electron beams, the phantoms are very similar to those for photon beams although compressed in depth because of the limited range of the incident 20 MeV mono-energetic electron beam. From 1 to 2 cm is water, 2 to 3 cm is aluminium, 3 to 6 cm is lung material and 6 to 30 cm is water. The results are to be compared with those of the EGS4/PRESTA calculation in this case. Typical precision is 0.2% of dose maximum.

RESULTS

1. Speed of photon calculations

The proposed phantom of 30.5 cm×39.5 cm×30 cm depth and filled with 5 mm^3 voxels was constructed using DOSXYZnrc code.[9] The material of the phantom was all chosen as water for simplicity. DOSXYZnrc is an EGSnrc-based Monte Carlo simulation code for calculating dose distributions in a rectilinear voxel phantom and is based directly on the DOSXYZ code developed for the EGS4 code system. Density and material in every voxel may vary. A variety of beams may be incident on the phantom, including full phase-space files form BEAMnrc and beams characterized using BEAM Characterization models. The companion program ctcreate is capable of reading in a CT data set of Hounsfield numbers and converting it into the information needed by DOSXYZnrc to simulate transport in a phantom (i.e. the appropriate material and density are specified in each voxel).

The Monte Carlo transport parameters used for the phantom calculation are 0.01 MeV for the photon cut-off energy (AP and PCUT) and 0.700 MeV for the electron cut-off energy (AE and ECUT). As soon as an electron's total energy falls below the cutoff energy; ECUT, its history is terminated and its energy deposited in the current region. For therapy beams, ECUT can be quite high since low-energy electrons contribute little to dose in phantom. It is generally accepted to use ECUT = 0.700 MeV for therapy beams. No range rejection was applied. When range rejection was applied with a kinetic cut-off energy of 5.0 MeV, only 5% of calculation time was reduced. The "overall" statistical uncertainty $\Delta\bar{D}$ of the simulation is defined as

$$\Delta \overline{D}^2 = \frac{1}{N} \Sigma \left(\frac{\Delta D_i}{D_i} \right)^2 \quad \cdots\cdots (1)$$

where Di is the dose in the ith region, ΔD_i the associated statistical uncertainty (1 σ), the summation runs over all voxels with a dose greater than 50% of the maximum dose and N is the number of such voxels. The result are summarized in Table 1, compared with that of other groups. 5×10^7 histories of incident photons were necessary to achieve statistical uncertainty less than 2%. The simulation was done with 40 parallel job processing on our Linux cluster system. The whole simulation of 5×10^7 incident photons were divided into 40 parallel batch jobs of 1.25×10^4 particles per each batch job and then distributed each computing node. For considering computing capabilities of two different CPU types, Each 650 MHz CPU then ran one of these job and each 1.2 GHz CPU ran two jobs at the same time. This parallel procedure was automatically performed by DOSXYZnrc batch job program, pprocess in conjunction with Generic NQS.

2. Speed of electron calculations

With the same phantom as photon beams, the 6 MeV and 20 MeV mono-energetic electron beam were simulated. The Monte Carlo transport parameters used for the phantom calculation are 0.01 MeV for the photon cut-off energy (AP and PCUT) and 0.521 MeV for the electron cut-off energy (AE and ECUT). The maximum fractional energy loss per electron step; ESTEPE was chosen as a default value, 0.25. No range rejection was applied. When range rejection was applied with a kinetic cut-off energy of 5.0 MeV, only 5% of calculation time was reduced.

For 6 MeV electron beam, 8×10^5 histories was necessary to reduce statistical uncertainty less than 2%. It took 58.5 minutes on a single P-III 500 MHz computer. However the net CPU time used for the same calculation on our Linux cluster system was 1.2 minutes, the overall time was 3.9 minutes, which included the distribution of batch jobs. Since the Monte Carlo simulation of electron beams is much faster than that of photon beams, the time overhead due to the batch job maintenance can be ignored in the clinical sence.

For 20 MeV electron beam, 106 histories was necessary to reduce statistical uncertainty less than 2%. It took 225 minutes on a single P-III 500. The net CPU time used in this calculation on our Linux cluster system was 4.5 minutes and the overall time for the whole procedure was 7.5 minutes. When range rejection was applied with a kinetic cut-off energy of 5.0 MeV; ESAVE, 57-8 % of calculation time was reduced for 6 MeV and 20 MeV electron beams.

Table 1. Comparison of speed to 6MV photon beam calculation with various codes. MCDOSE and VMC++ code systems are far more efficient than the original DOSXYZ code using a single CPU. However, our Linux cluster system shows comparable performance with these code systems

	our system		MCDOSE (ref. 2)	VMC++ (ref. 3)
	single 500 MHz	Linux-cluster		
Time (min.)	273	5.5	9.5	5.55

3. Accuracy of photon calculations

The reference data provided by the NRCC is the results of the EGS4/PRESTA/DOSXYZ (ESTEPE) = 0.01(electrons) or default (photons), AE=0.521, ECUT= 0.700 MeV) calculations.

To test accuracy of photon calculations, we simulated 5×10^7 histories of 18 MV photon beam for a 1.5×1.5 cm^2 beam from a uniform point source at 100 cm incident on the phantom and the dose is scored on the central axis in 5×5 mm^2 voxels which are 2 mm thick in the beam direction. The statistical

uncertainties were less than 0.5 %.

Since Monte Carlo code used on our Linux cluster system are BEAMnrc code system, which is based on EGSnrc code, it does not have much meaning on the difference between results of BEAMnrc calculation of this study and the reference EGS4/PRESTA calculations.

Figure 3 presents comparison of the results as calculated with EGSnrc in this study for the 18 MV photon beam case and with the reference EGS4/PRESTA. The direct comparison in Fig. 3 is not very informative since the difference are small compared to the scale whereas Fig. 4 presents two other comparisons of the data. The absolute difference as a fraction of the dose maximum shows that even for these two very slow codes there are some differences but they are limited to a few tenths %. Plotting the ratio of the two calculations vs depth shows that the codes diverge but this is for such small doses that it is not important.

Fig. 4 shows the difference in dose vs depth calculated by EGSnrc in this study less that calculated by EGS4/PRESTA as a fraction of the dose maximum (filled squares). Ratio of EGSnrc dose/EGS4-PRESTA dose -1.0 (opoen joined squares). Typical difference were 2%.

4. Accuracy of electron calculations

The EGSnrc has been improved after the beanchmark held at the XIII ICCR, especially the multiple scattering and spin correction was added to the code. The spin correction takes into account relativistic spin effects of the elastic scattering cross-sections during electron transport. This spin correction makes a distinct effect on calculated depth-dose curves of electron beams. In low-Z materials such as water, the value of R50 for a given energy is higher than with EGS4/PRESTA. For high-Z materials it is the reverse and backscatter also increases. This effect is well presented at Fig. 5 and Fig. 6.

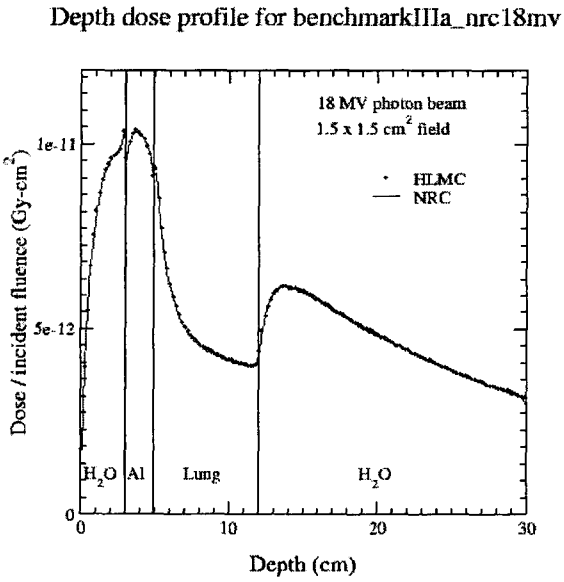

Fig. 3. Comparison of depth-dose curves for the 18 MV photon case as calculated by EGSnrc of this study (1σ of 0.5%) and EGS4/PRESTA.

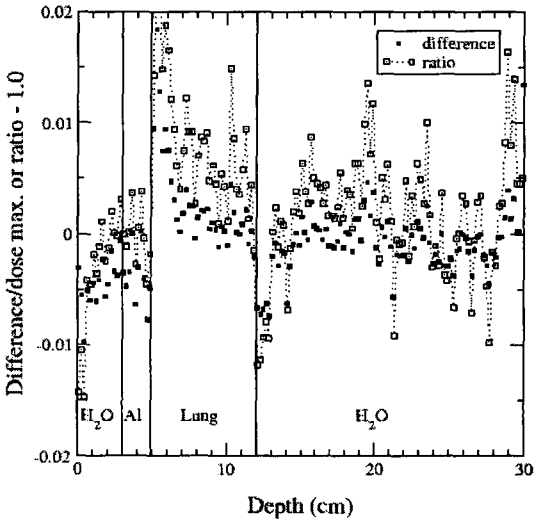

Fig. 4. Difference in dose vs depth calculated by EGSnrc in this study (1σ of 0.5%) less that calculated by EGS4/PRESTA as a fraction of the dose maximum (filled squares). Ratio of EGSnrc dose/EGS4-PRESTA dose -1.0 (opoen joined squares).

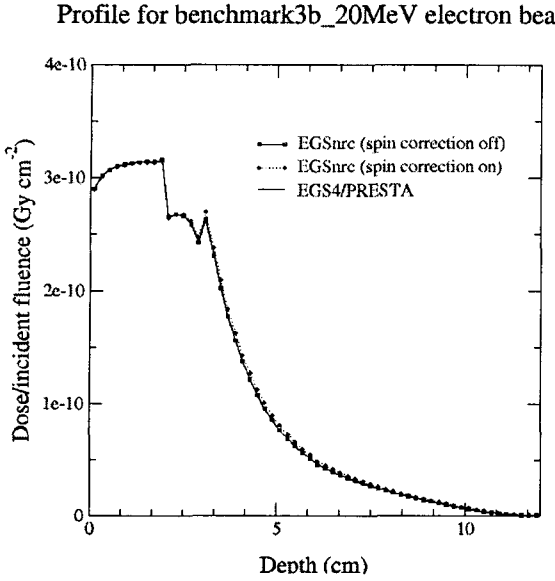

Fig. 5. Comparison of depth-dose curves for the 20 MeV electron case as calculated by EGSnrc of this study (1σ of 0.5%) and EGS4/PRESTA. Since EGS4/PRESTA does not take into account relativistic spin effect for elastic scattering cross-section during electron transport, there is a systematic difference when the EGSnrc calculation takes into account this effect.

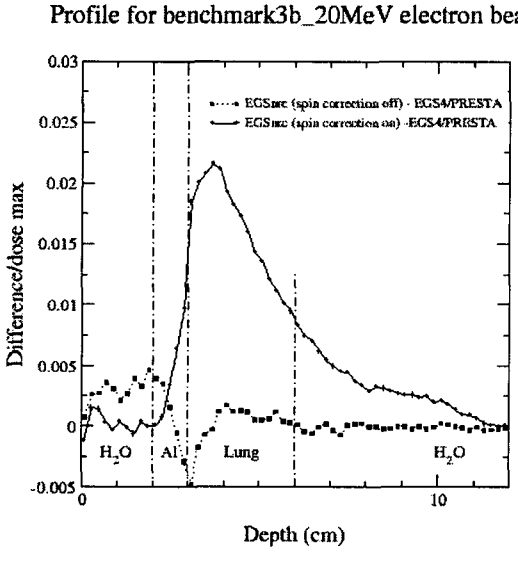

Fig. 6. Difference in dose vs depth calculated by EGSnrc in this study (1σ of 0.3%) less that calculated by EGS4/PRESTA as a fraction of the dose maximum. Since EGS4/PRESTA does not take into account relativistic spin effect for elastic scattering cross-section during electron transport, there is a systematic difference when the EGSnrc calculation takes into account this effect.

CONCLUSION AND DISCUSSION

With the benchmark tests proposed at the XIIIth ICCR, Our Monte Carlo treatment planning system shows clinically meaningful results, i.e. our Linux clusered Monte Carlo system can calculate dose distributions of photon beams in the phantom 30.5 cm×39.5 cm×30 cm deep and filled with 5 mm^3 voxels within 6 minutes and 2% statistical uncertainty.

Though other more efficient codes are developed such like MCDOSE and VMC++, BEAMnrc based on EGSnrc code system may be used for routine clinical Monte Carlo treatment planning in conjunction with clustering technique. This system will be further developed to be able to interface with our commercial treatment planning system, Pinnacle (Philips, USA) and provide an integrated treatment planning environment in which issues related to clinical implementation of Monte Carlo based treatment planning could be addressed.

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몬테카를로 기반 치료계획시스템의 성능평가

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조 병 철

최근 들어 방사선 수송이론, 컴퓨터 하드웨어 성능, 및 병렬 연산 기법의 발전에 힘입어, 몬테카를로 기반의 선량계산 기법을 임상에 적용할 수 있게 되었다. 임상적용을 위해 개발된 몬테카를로 기반 선량계산 코드간의 계산 소요 시간과 정확도를 비교할 목적으로 제13차 ICCR (International Conference on the use of Computers in Radiation Therapy, Heidelberg, Germany, 2000) 학술대회에서 벤치마킹 절차서가 제안되었다. 최근, 본원에서도 임상적용을 목표로 28개의 인텔 펜티움 프로세서로 구성된 Linux cluster 시스템을 구축하고, 여기에 몬테카를로 선량계산을 위한 BEAMnrc 코드를 설치하였다. 본 연구의 목적은 위에서 제안된 벤치마킹 절차를 수행하여 본원에서 구축한 몬테카를로 선량계산 시스템의 정량적 성능 평가를 시도하고자 하는 것이었다. 벤치마킹 절차는 크게 다음의 세 과정으로 구성되어 있다. a) 30.5 cm×39.5 cm×30 cm 의 팬톰(5 mm^3 voxels) 에 대한 통계적 불확정도 2%이내 결과를 얻기 위한 광자선 선량계산 속도. b) 위 팬톰에 대한 전자선의 선량계산 속도. c) 비균질 평판 매질로 구성된 팬톰내 광자선 및 전자선의 선량계산 결과를 EGS4/PRESTA 계산 결과와 비교 제시. 18 MV 광자선에 대해 선량계산 속도 평가 결과 5.5분이 소용되었다. 전자선의 경우, 실제 계산 시간은 광자선에 비해 약 10배 정도 빨랐으나, 병렬 연산을 처리하기 위해 소용되는 추가 시간 때문에 전체 계산에 소요되는 시간은 광자선과 비슷하였다. 본 원에서 사용한 몬테카를로 코드는 EGSnrc로써 EGS4의 개선 버전으로 이들 간의 정확도 비교는 큰 의미가 없을 것으로 판단된다. 하지만 두 계산 결과가 기대했던 바와 같이 매우 잘 일치하였다. 결론적으로, 본원에서 구축한 몬테카를로 치료계획시스템은 임상적용에 무리가 없을 것으로 판단하였다. 추후 본 시스템을 본원에서 사용하는 상용 치료계획시스템과 인터페이스를 개발하여, 통합환경을 구축함으로써, 몬테카를로 기반의 치료계획시스템의 임상적용과 관련된 연구들을 수행해 나갈 계획이다.

중심 단어 : 몬테카를로, 방사선치료계획시스템, 벤치마크