THE MONTE CARLO SRNA CODE AS THE ENGINE IN ISTAR PROTON DOSE PLANNING SOFTWARE FOR THE TESLA ACCELERATOR INSTALLATION

by

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Received on August 27, 2004; accepted in revised form on September 21, 2004

This paper describes the application of SRNA Monte Carlo package for proton transport simulations in complex geometry and different material composition. SRNA package was developed for 3D dose distribution calculation in proton therapy and dosimetry and it was based on the theory of multiple scattering. The compound nuclei decay was simulated by our own and the Russian MSDM models using ICRU 63 data. The developed package consists of two codes: SRNA-2KG, which simulates proton transport in the combinatorial geometry and SRNA-VOX, which uses the voxelized geometry using the CT data and conversion of the Hounsfield's data to tissue elemental composition. Transition probabilities for both codes are prepared by the SRNADAT code. The simulation of proton beam characterization by Multi-Layer Faraday Cup, spatial distribution of positron emitters obtained by SRNA-2KG code, and intercomparison of computational codes in radiation dosimetry, indicate the immediate application of the Monte Carlo techniques in clinical practice. In this paper, we briefly present the physical model implemented in SRNA package, the ISTAR proton dose planning software, as well as the results of the numerical experiments with proton beams to obtain 3D dose distribution in the eye and breast tumor.

Key words: Monte Carlo proton transport, 3D geometry, CT patient anatomy, proton dose planning software

INTRODUCTION

During past twenty years, special attention has been paid to the development and implementation of Monte Carlo calculation in radiation protection, spectral distribution calculations and particularly in medicine. Recently, various commercial versions of Monte Carlo algorithms have started being implemented in practice and it has become obvious that Monte Carlo represent a convenient computing method with significant clinical application.

There is the increasing evidence that Monte Carlo based codes are the most powerful tools for nuclear particle transport calculations. A growing number of medical physicists believe that, in the future, routine dose calculation will be performed using Monte Carlo techniques, which will prove to be the dominant engine for dose computation in radiotherapy treatment planning [1, 2]. The most powerful attribute of Monte Carlo techniques is their capability to simulate all individual particle interactions in three dimensions as well as to perform numerical experiments with specified uncertainties. In the frame of design and construction of the TESLA Accelerator Installation at VINČA Institute of Nuclear Sciences, it became necessary to develop a special code suitable for proton radiation. These facts were the primary motivation for development of SRNA* – general-purpose Monte Carlo package for proton transport simulation. A wide

Scientific paper
UDC: 615.849.5:539.125.4:519.245
BIBLID: 1451-3994, *19* (2004), 2, pp. 30-35

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*srna = doe (Engl.)

range of SRNA applications required the development of two codes such as SRNA-2KG code and SRNA-VOX code. The first one is assigned to proton transport simulations in technical systems determined by standard geometrical forms (sphere, cone, cylinder, cube). The second one is designed for calculations of deposited energy distribution in patients based on CT data for radiotherapy purposes. It is possible to use both codes in the case of 3D proton sources with an arbitrary energy spectrum from 100 keV up to 250 MeV. Transition probabilities are prepared by SRNADAT code.

The correctness of the physical model implemented into SRNA package was verified either through direct comparison with other referent codes for proton transport simulation, or through experiments. The most recent results of verification are listed bellow. Great degree of reliability of the proton simulations carried out by SRNA package, motivated us to develop ISTAR proton dose treatment planning software examined through the eye and breast tumor irradiation planning.

SRNA package and ISTAR proton dose planning software are coded in Fortran 77 and run on PC under the Windows and Linux operating systems.

SRNA PACKAGE VERSIONS AND THEIR VERIFICATIONS

SRNA proton transport model

The simulation of proton transport in SRNA package is based upon the multiple scattering theory of charged particles [3-5], energy losses with fluctuation [6, 7], and our own and Russian MSDM models of compound nucleus decay simulation after proton absorption in inelastic nuclear interactions. The further details of this model can be found in the basic reference [8]. Only a brief overview is given here. In order to simulate the proton transport, the proton trajectory is divided into small steps with length designated s as followed by a small energy loss E chosen to be several percent of the initial proton energy. The model implemented in PTRAN code [9] gives the best results with combined energy scale: logarithmic from 100 keV up to 10 MeV and linear for energy up to 250 MeV. The stopping power ($\mathrm{d}E/\mathrm{d}x$) can be obtained from ICRU 49 data base [10]. If the particular value for ($\mathrm{d}E/\mathrm{d}x$) is not available in the data base, it is calculated according to the empirical formulae [11].

After the preparation, the nominal energy scale is modified so that the average number of collisions over the step Δs is greater than the minimal value ($\Omega > 10$), and the Vavilov's parameter κ is smaller than the maximal value ($\kappa < 20$). The modified energy scale is then used for calculation of: Vavilov's energy loss distribution, multiple scattering Moliere distribution and all inelastic nuclear interaction distributions (according to the cross section data from ICRU 63 and from SCHIELD code [12, 13]). Only secondary protons are included in the transport simulation model, while the energy of deuterons, tritons and alpha particles is deposited on the spot of their creation. Neutrons and photons are registered in a data file and can be further used by MCNP code [14] with the aim to simulate the neutron and photon transport, or by FOTELP [15] and PENELOPE [16] codes for photon shielding and dosimetry calculations.

Particle transport simulation is limited by the geometrical description of the transport medium. Real geometric shapes of technical systems could be described in several ways by planes and second order surfaces, as in RFG [17] or PENGEOM from PENELOPE codes and fourth order surfaces, as in MCNP code. For description of the patient geometry, standard shapes are usually applied. However, this is only a rough approximation, because it is a technical description of the patient's geometry. The most accurate way of describing it is by means of the CT data [1, 18]. They allow 3D transport simulation, including variations of the tissue densities and compositions. Using the same proton transport model, we developed two versions of SRNA code. The first version uses the RFG or PENGEOM codes for geometric modeling. The second, voxelized version, SRNA-VOX, is adjusted to use the CT data.

The problems concerning the determination of density and elemental composition of the patient's tissue on the basis of the CT data, for Siemens Somatom Plus 4 scanner, are described elsewhere. In our model, the Hounsfield's numbers (HU) are associated to the density and the elemental tissue composition [18].

The HU space is divided into 21 groups. HU values less than –950 are treated as air. Each remaining group from HU = –950 to HU = 1500 has the density and elemental composition suitable for the group's upper limit. Starting from such presentation of HU, we use SRNADAT code to prepare all previously mentioned transition probabilities for the proton energy range from 0.1 up to 250 MeV, for all tissue types. From the entire available CT data only the part that contains the region of interest for irradiation planning is extracted, and consequently only the data for the selected region are processed and stored in the computer memory.

Verification of SRNA package

The first verification of SRNA package performed for proton energies of 26.4, 66, 100, 205, and 250 MeV, is based on the good agreement with

the results obtained by the referent proton transport codes [8]. Numerical experiments performed by SRNA-2KG and GEANT-3 codes, as well as by SRNA-2K3 and GEANT-4 codes gave an additional confirmation that our proton transport model is consistent. The simulation and measurement [19] of proton beam energy spread using Multi-Layer Faraday Cup at IUCF, Indiana University, as well as the simulation of positron emitter generation [20] at Brookhaven National Laboratory contributed to the evidence that SRNA package could be successfully applied for dosimetry and radiotherapy purposes. The final stage of SRNA-2KG verification was QUADOS intercomparison [21] of proton transport codes. The results obtained by our code, using an artificial voxelized eye model, were compared to those obtained by FLUKA-2002, being the referent code of the mentioned intercomparison. Very good agreement of results encouraged us to develop the SRNA-VOX code as an engine within ISTAR software for proton therapy planning.

TESLA ACCELERATOR INSTALLATION

The TESLA Accelerator Installation is a facility for production, acceleration and use of ions consisting of three machines and a number of low energy and high energy experimental channels. The machines are the VINCY Cyclotron – a compact isochronous cyclotron, the mVINIS Ion Source – an electron cyclotron resonance heavy ion source, and the pVINIS Ion Source – a volume light ion source. In the low energy experimental channels one shall be able to use ion beams from the mVINIS Ion Source, and in the high energy experimental channels ion beams from the VINCY Cyclotron. Programs of use of this facility include basic and applied research in physics, chemistry and biology, development of materials and nuclear technologies, production of radioisotopes and radiopharmaceuticals, and proton therapy 22 . The first program of use of the VINCY Cyclotron will be routine production of radionuclide ^{18}F and radiopharmaceutical ^{18}FDG. This radiopharmaceutical will be used for positron emission tomography, which is an advanced diagnostic technique used in oncology, cardiology, endocrinology, and neurology. Radionuclide ^{18}F will be produced with protons of the energy of 15 MeV. Proton therapy will be performed with the beam from the VINCY Cyclotron of the energy of 65 MeV. It will be used for eye tumor treatments. As the SRNA code was designed for protons of the maximal energy of 250 MeV, it will be a suitable tool in planning of proton therapy with this machine.

In proton experiment planning, it is understandable that a proton beam is determined by the shape of a channel, and that targets in the beam are space adjustable according to experiment conditions. For numerical experiments, it is reasonable to accept a fixed target, and that a proton beam should be within the space angle of 4 , according to the symmetrical axis of the target. The accelerator target geometry is complex, and protons arrive at targets with an arbitrary spectrum. Some of the applications of developed SRNA code used in TESLA program are: proton therapy, design of accelerator driven systems, radioisotopes production for medical applications, simulation of proton scatterer and degrader shapes, and composition as well as radiation protection at accelerator installations.

ISTAR – PROTON DOSE PLANNING SOFTWARE

Last few years, the attention of medical physicists was focused on possible applications of Monte Carlo techniques for radiotherapy planning in general, and especially for proton therapy. In the clinical practice, available anatomy imaging techniques are nearing the desirable geometric resolution for definition of the tumor shape and dimensions, necessary for therapy planning.

Such trends lead to solving two important problems in proton therapy planning: (1) development of Monte Carlo proton transport numerical engine capable of producing a therapy plan in less than 30 minutes and (2) development of clinically acceptable on-line procedures comprising all steps necessary for proper patient treatment. In the following, the capability of ISTAR software in solving the first of these problems is presented.

ISTAR has a capability of working with two CT files simultaneously, so that the user can switch between them during a computing session. This is illustrated in fig. 1, where breast and eye CT images are taken as examples. It is assumed that the tumor location is defined using the CT image with sufficient accuracy. The irradiation plan begins with the selection of the tumor region within a rectangular box. The selected region is defined by the indices of the first and the last CT slice in the longitudinal (Z) direction, and by marking the area in the transversal (X-Y) plane. The beam center position, defining the position of the proton beam axis, should be selected at this step, together with the proton energy distribution (mean energy and standard deviation for Gaussian distribution, or custom defined spectrum), simulation cutoff energy, number of proton histories and simulation time limit.

The appropriate transition probabilities are prepared only for the materials in the tissue selected for irradiation. The transport of the protons is simulated in batches (typically 20), performing statistical analysis

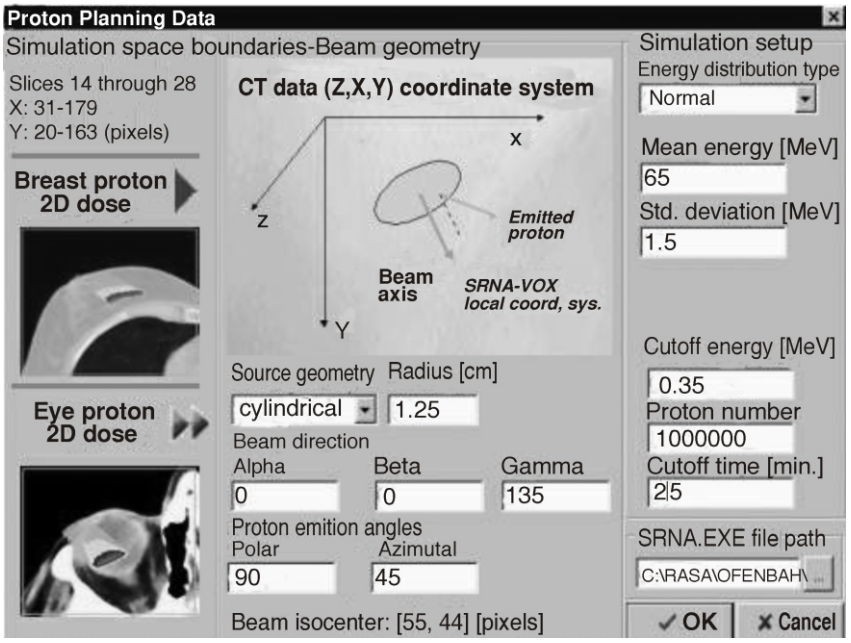

Figure 1. Proton Planning Date window (Interested reader can obtain more detailed color pictures at the author's address)

of the scores after each single batch. The absorbed dose in each voxel is stored in a 3D matrix, which is appropriate for further numerical manipulation. The calculated values of the absorbed proton dose are displayed over the CT slice image. These values can be normalized either to the maximum value in the slice, or to the maximal value in the entire irradiated region. Image viewing commands include a transparency intensity control. The code allows selection of different palettes, for displaying various isodose levels.

RESULTS

Taking into consideration that the previous results of the verification of SRNA package concern only the proton transport simulations in water phantoms, and that the considered geometries were relatively simple, in this paper we have decided to treat some more realistic cases, both in shape and material composition. As for the proton energies, they are chosen to correspond to the proton beams which will be available from the VINCY Cyclotron at the TESLA Accelerator Installation [20]. The capabilities of ISTAR proton dose planning software are illustrated in the following two examples: eye *uvela melanoma* and breast tumor, using 1.6 GHz/512 MB PC.

Eye dose distribution

The CT of the patient's head with voxel dimensions of 0.5 0.045 0.045 cm^3 was used. The melanoma was assumed to be at the bottom of the eye, spherically shaped with a radius of 0.8 cm. Using ISTAR software, a therapy plan was made using a cylindrical proton beam of 1 cm radius and Gaussian energy spectrum ($<E> = 50$ MeV, energy spread 1.2 MeV). The simulation was performed with 10^6 proton histories. Figure 2 shows the proton dose distribution on a slice in the equatorial plane of the eye. Similar figures can be produced for each slice above/below the equatorial plane, within the boundaries of the selected region. This simulation took 7.62 minutes on the aforementioned PC.

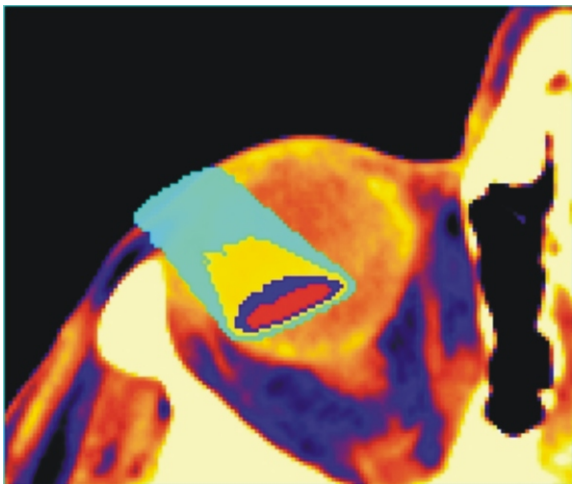

Figure 2. Dose distribution in equatorial eye plane, simulated by SRNA-VOX code, using 50 MeV protons with 1.2 MeV energy spread. The isodoses are at the values of 20, 60, 80, and 100% of dose maximum

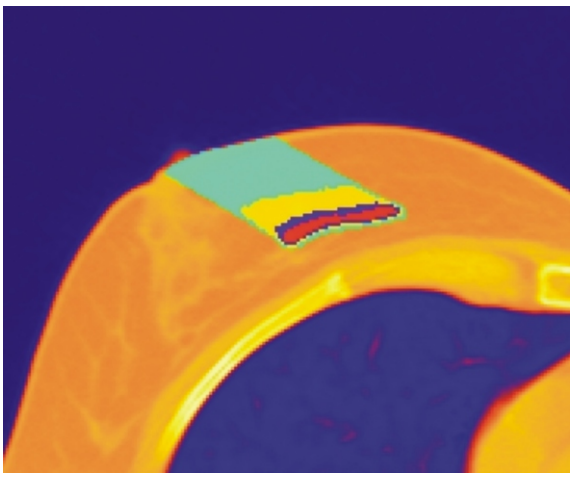

Figure 3. Dose distribution in breast in the central beam plane simulated by SRNA-VOX code using 65 MeV protons with 1.5 MeV energy spread. The isodoses are at the values of 20, 60, 80, and 100% of dose maximum

Breast dose distribution

As the second example, a CT image of a breast with voxel dimensions of 0.5 0.0732 0.0732 cm^3 was chosen. A therapy plan with a cylindrical proton beam of 1.2 cm radius and with Gaussian energy spectrum (<E>= 65 MeV, energy spread 1.2 MeV) and 10^6 protons in the beam was used. The resulting proton dose distribution is displayed in fig. 3. Simulation run-time on the aforementioned PC was 9 minutes.

CONCLUSIONS

The development of SRNA package has been going on by continual upgrading of the implemented physical model, broadening of the proton energy range, and increasing the efficiency of the implemented algorithms in order to decrease the time necessary for proton transport simulation. In parallel with this subsequent verification the main steps of improvement were carried out by comparison with the referent codes for proton transport simulations. Unfortunately, comparison with measured or calculated results in 3D heterogeneous phantoms was not done since we didn't find any such results in the available literature. The results of this verification proved the consistency of the model implemented in SRNA package, and motivated us to develop ISTAR proton dose planning software, based on the knowledge and experience acquired in working on SRNA package. Additional motivation was the fact that typical execution time for the Monte Carlo based codes on common PC computers in everyday clinical practice was getting substantially shorter, thus removing the main obstacle for introducing them. In its present status, ISTAR is capable of accepting CT data for defining patient's anatomy and tissue composition. A simple procedure for selecting the irradiation area and incident proton beam parameters allows fast and comfortable calculation of the dose distribution and its visualization in each CT recorded slice of the patient's body. Acceptable statistical uncertainty of the calculated dose can be reached within 30 minute of computer run time. The future activities in the upgrading of ISTAR software will include visualization of the dose distribution over a 3D transparent model of the patient body.

ACKNOWLEDGMENTS

This work is supported by the Ministry of Science and Environmental Protection of the Government of Serbia through the TESLA Project (No. 1247) and Physics of Radiation Protection contract (No 2016). We are grateful to Dr. Nebojša Nešković and Dr. Jožef Čomor from the TESLA Accelerator Installation, Laboratory of Physics, Vinča Institute of Nuclear Sciences, for valuable comments on the manuscript.

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**Радован Д. ИЛИЋ, Весна СПАСИЋ-ЈОКИЋ,
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SRNA – МОНТЕ КАРЛО ПРОГРАМ КАО АЛАТ ISTAR СОФТВЕРА ЗА ПЛАНИРАЊЕ ТЕРАПИЈЕ ПРОТОНИМА НА АКЦЕЛЕРАТОРСКОЈ ИНСТАЛАЦИЈИ ТЕСЛА

Описана је примена SRNA – Монте Карло пакета за симулацију протона у сложеној геометрији и материјалима различитог састава. Пакет SRNA је развијен за тродимензионални (3D) прорачун расподеле дозе у протонској терапији и дозиметрији и заснован је на теорији вишеструког расејања. Распад сложеног језгра је симулиран нашим сопственим и руским MSDM моделом коришћењем података из ICRU 63. Развијени пакет се састоји од два програма: SRNA-2KG који симулира транспорт протона у комбинованој геометрији и SRNA-VOX који користи вокселизовану геометрију применом CT података и конверзијом Хаунсфилдових бројева за ткива различитог састава. Вероватноће прелаза за оба програма припрема програм SRNADAT. Симулација карактеризације протонског снопа коришћењем вишеслојног Фарадејевог кавеза и просторне расподеле емитера позитрона добијена SRNA-2KG програмом и интеркомпарација рачунских програма у дозиметрији наговештавају директну примену Монте Карло техника у клиничкој пракси. У овом раду смо укратко приказали физичке моделе примењене у пакету SRNA, софтвер за планирање протонске дозе ISTAR и резултате са њим изведених нумеричких експеримената за добијање 3D расподеле дозе у туморима ока и дојке.