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MONTE CARLO SIMULATION OF PROTON TRANSPORT AT THERAPEUTIC ENERGIES*

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Physical and biological characteristics of protons as well as technical requirements on proton beams are reviewed in order to illustrate the need for accurate proton transport simulations for therapeutic applications. Certain Monte Carlo proton transport simulation codes that have been used at therapeutic energies are briefly discussed. A general insight into two proton transport simulation schemes is presented; one including the generation and transport of secondary protons and the other comprising the generation and transport of secondary electrons. Based on different experiences gained, an analysis of the role of secondary particles is given.

Key words: *Monte Carlo simulation, proton transport codes, characteristics of protons, secondary particles, therapeutic energies, dosimetry, proton biomedical applications*

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THERE has been an increased interest in the application of proton beams in radiation therapy in the last decade, although they have been in use since the mid 50's. This is due to a continuous increase in number of accelerators in operation and in data for protons at lower energies, *i. e.*, energies ranging from 50 to 250 MeV, which are in fact the energies commonly used in proton therapy.

The advantage of proton beams compared to the conventional therapy, *i. e.*, photons and electrons, lies in their physical properties: well defined range, relatively small lateral scattering and, most importantly, high energy deposition density or dose just before the end of the range. The depth-dose curves for photons and electrons are characterized by a rapid build-up to a maximum which is close to the entrance point, followed by a near exponential fall-off. Thus, the maximum dose is delivered more superficially and there is still a substantial dose beyond this maximum. This can be contrasted with the depth-dose curve for the monoenergetic proton beam. Here, there is a slow increase of the dose in the plateau region, followed by a rise to a well-defined dose maximum at the Bragg peak. Beyond the Bragg peak, the dose rapidly falls to zero. This Bragg peak and the rapid distal fall-off provide a good localisation of the dose in depth and demonstrate a clear physical advantage over the photon and electron curves at all depths other than those immediately after entering the medium. Such behavior of the protons can be roughly explained in the following way. The energy transferred by a proton to a quasi-stationary electron is inversely proportional to its velocity square. The ionization density (called LET, linear energy transfer) rises as the proton slows down until, at the very end of the range, the proton charge is neutralized by electron pick-up and the ionization falls very rapidly to zero. This gives rise to the ionization curve where the maximum dose is delivered in a narrow peak at the end of the range at a position that can be precisely controlled. By varying the incident energy of protons the position of the Bragg peak varies in depth, which implies that higher proton energies are needed to achieve the range required to reach deep-seated tumours in tissue. The described qualities of proton beams make them particularly suitable when malignant growths are deeply embedded or are close to critical organs, where there is a high demand for accurate dose delivery to minimize the destruction of the neighboring and overlaying tissue.

However, from the biological point of view, the difference between protons and photons or electrons is not important. To compare different biological responses produced by radiation of different quality the term relative biological efficiency (RBE) was introduced and defined as the ratio of the X-ray dose to the particle dose which produce

the same biological effect. RBE of protons depends partly on their energy, increasing with energy decreasing down to about 1 MeV, while below this energy it decreases due to the overkilling of cells. Moreover, it has been observed that various cell types react differently to variations in LET and thus to energy; some are more easily affected than others. Even at the proton energies of about 1 MeV RBE values below 2 have been found. RBE values in proton therapy are usually in the range of 1.1 to 1.2.

A small fluctuation in the absorbed dose will cause a relatively much more important change in the probability for tumour control or complications. This is due to the fact that the dose-response curve for tumour control and the dose-complication curve for surrounding healthy tissue are generally steep. Consequently, in proton therapy accurate dosi-metry is indispensable.

The proton beam extracted from an accelerator is very narrow and almost monoenergetic, although some energy spread exists. To be used in proton therapy for treating a target volume it has to be modified, *i. e.*, spread out both in depth and laterally so that it can deliver a dose over a large volume. The Bragg peak is only a few millimeters wide and must be broadened in order to give a uniform dose to a tumour which may be several centimeters thick. This beam modulation in depth is achieved by superimposing a number of proton beams of varying energies. As the energy is reduced, the position of the Bragg peak in depth is pulled back towards the beam source. By varying the relative weight of each superimposed beam, a so called Spread-Out-Bragg-Peak (SOBP), having a flat dose distribution, can be produced. In practice, beam energy is most easily modulated by passing the beam through a variable absorber, a range shifter, for example, a wheel of varying thickness rotating in the beam. To obtain dose spreading and thus create a treatment field, lateral broadening of the beam is most commonly achieved using a shaped scatterer and a flattening filter.

OVERVIEW OF CODES FOR PROTON TRANSPORT SIMULATION

The objective of calculating penetration, diffusion and slowing down of proton beams in different media is to provide necessary information for accurate treatment planning and dosimetry as well as for beam preparation in proton therapy. These calculations should give as a result the deposition of energy as a function of depth and radial distance from the beam axis, the energy spectra of protons as a function of depth, as well as the three-dimensional proton fluence and the stopping-power distributions as functions of depth.

Unfortunately, until recently there was a deficiency in computer codes appropriate for the simulation of proton transport at lower energies, *i. e.*, energies of therapeutic interest, which range from 50 to 250 MeV. The majority of the codes, based on the Monte Carlo method, that were available have been initially developed for detector modelling in high energy physics, for example, LAHET [1] and the former version of FLUKA. Therefore, the physics at lower energies was not treated with sufficient care to be used for current application in radiotherapy and its dosimetry. Moreover, these codes did not take into account the generation of secondary particles along the proton track in matter nor did they consider their influence on the combined particle fluence. In addition, the cut-off energy in proton transport was usually too high.

However, the interest for the simulation of proton transport at lower energies has increased in recent years. This led to improvements in the existing codes, as is the case with FLUKA94 [2] and GEANT [3]. Also, work on the development of new Monte Carlo codes was undertaken, for example, PTRAN [4] and PETRA [5]. In the FLUKA94 code major improvements regarding lower energies comprise: an upgraded stopping-power calculation including detailed δ-ray emission, a new model based on the multiple-scattering theory, a refined nuclear model and a decreased transport cut-off energy enabling proton transport down to the Coulomb barrier for nuclear interactions. Recently the GEANT code has been frequently used at therapeutic energies, although it was initially developed as a detector description and simulation tool for high energy physics. Its efficacious geometrical package is particularly appropriate for the simulation of beam transport in complex geometries and thus for the design of devices serving to shape and modify the beam for different applications [6, 7]. The code can be considered as a very detailed proton transport simulation tool due to its models for nonelastic nuclear interactions and the production of secondary electrons in single proton-electron collisions. But, the proton stopping-power data used in this code, which are also used in the FLUKA 94 code, are based on mean excitation energies [8] that are not up-to-date and may be therefore considered as obsolete since they can induce a discrepancy of several percent in the proton range. The PTRAN code is probably the most advanced proton transport Monte Carlo code at therapeutic energies. It uses the new ICRU 49 [9] stopping-power data for proton energy loss. The code takes into account the removal of protons from the beam due to nonelastic nuclear interactions, but the secondary protons created, as well as heavier charged particles, deliver their energy locally at the site of interaction. However, it does not take into account the production

and transport of secondary electrons which can affect proton dosimetry when using the ionization chamber. Since the code can perform only proton transport in water, it is consequently not applicable for simulations in complex heterogeneous geometries. It should be noted that water is often considered as a tissue equivalent material. The PETRA code is probably the most recent proton transport code. It pays particularly attention to the production and transport of secondary electrons created along the proton track. The code also includes the simulation of nonelastic nuclear collisions as well as the transport of secondary protons created in these interactions. The proton stopping-power data are obtained from ICRU 49. But, the code considers only one-dimensional proton transport in water. To the author's knowledge, other Monte Carlo codes designed to simulate proton transport in matter have not been extensively used for applications in the field of proton therapy.

In the past, rather poor and not sufficiently accurate data libraries for protons at lower, *i. e.*, therapeutic, energies represented an important drawback in the field. There was especially a lack of data for different materials concerning nonelastic nuclear interactions and secondary particles created in these reactions. Therefore, there was a lack of basic data needed to achieve the desired accuracy in the proton dosimetry: mean energy for the production of an ion pair in a detector, dose conversion factor for the derivation of the absorbed dose in a medium, correction factors to account for the perturbation of particle fluence caused by inserted detector, *etc.* But, at present the situation is changing and more and more data are available particularly regarding nonelastic nuclear interactions.

SIMULATION OF PROTON AND SECONDARY PARTICLE TRANSPORT

Solving the transport problem for protons is mathematically complex since a variety of interactions may have to be considered jointly: inelastic scattering by atomic electrons, production of secondary knock-on electrons, elastic scattering by atomic nuclei, nonelastic nuclear interactions and production of secondary particles in these interactions. Inelastic collisions with atomic electrons are almost solely responsible for the energy loss of protons in matter. In these collisions energy is transferred from the proton to the atom causing an ionization or excitation. The amount transferred in each collision is generally a very small fraction of the total kinetic energy of the proton, but the number of collisions per unit path length is so large that a substantial cumulative energy loss is observed even in thin layers of matter. Elastic collisions with nuclei also occur frequently although not as often as electron collisions. In general, very little energy is transferred in these collisions since the masses of the nuclei are large compared to the proton. The total probability per unit path length for a nonelastic nuclear collision is very small, however, these collision do play an important role in the energy loss process. Nevertheless, the major part of the energy loss is still due to atomic electron collisions. In addition, due to the much larger mass of the proton with respect to the electron it is usually considered that after a proton-electron collision, the proton is undeviated from its original path. Thus, the angular deflection of a proton from its initial direction, while traversing matter, is attributed to elastic collisions with nuclei and is quite small.

Two proton transport simulation schemes that seem to be appropriate and efficient for therapeutic energies are presented here. In the first scheme, apart from the transport of primary protons, generation of secondary protons in nonelastic nuclear interactions and their transport are considered. The second scheme comprises the transport of primary protons, generation and transport of secondary protons, but also includes the generation of secondary electrons in inelastic collisions with atomic electrons and their transport. These schemes are to a certain extent included in the mentioned codes.

Simulation of primary and secondary proton transport

When traversing even a thin layer of matter a proton (similarly as an electron) will have an enormous number of collisions so that an analogue Monte Carlo simulation, usually employed for neutron or gamma-ray transport (since the number of their collisions in matter is drastically smaller), would be laborious and very time-consuming. Obviously, deterministic methods which are efficiently used in neutron transport [10, 11, 12] cannot be used in this case. An efficient alternative, commonly used in Monte Carlo proton transport simulation codes, is based on the grouping of many steps of the actual physical random walk into a single step of a condensed random walk [13]. In this way a condensed history is sampled by letting the proton carry out a random walk in which each step takes into account the combined effect of many collisions. Proper multiple-scattering theories are used to provide transition probabilities for the condensed random walk. To enable a large number of walks being sampled in a reasonable amount of time the number of steps in a walk are kept small enough and thus affect grouping. The Monte Carlo problem that remains to be solved resembles those appearing in usual random sampling procedures of neutron or

gamma-ray transport problems. Even if the geometry of the medium is complex it is rather easy to set up computations, although they are quite time-consuming and need a large number of predigested information to be evaluated and stored in the computer memory. Thus, it seems that this is a problem of data processing rather than of analysis. However, the multiple-scattering theories implemented in the Monte Carlo scheme are not quite thorough and combined with the effects of grouping induce certain arbitrariness. This introduces a systematic error that is superimposed on the statistical error related to random sampling.

The size of the steps of the random walk, *i. e.*, the path-length intervals, must be chosen with particular care. The steps should be as large as possible to reduce the computing time. At the same time they should be small enough to reduce the error resulting from neglecting individual collisions. Also they should be small enough in order that the energy loss per step is a small fraction of the energy at the beginning of the step. The steps must be chosen in such a way that the energy straggling distribution and the multiple-scattering distributions can be applied. In fact, the path-length plays the role of an energy parameter in the continuous slowing-down approximation and is defined as:

$$\Delta s_n = \int_{E_{n+1}}^{E_n} \left| \frac{dE}{ds} \right|^{-1} dE \qquad (1)$$

where dE/ds is the stopping-power, *i. e.*, the mean energy loss per unit path-length. The stopping-power is taken as the sum of two contributions; the interaction of proton with atomic electrons (called electronic or ionization stopping-power) and with nuclei (called nuclear stopping-power). The choice of the path-length size is made via the adoption of an energy grid for which cross sections and probability distributions are evaluated. Since protons lose only a tiny fraction of their energy in an individual collision and thus cross a practically continuous range of energies it is quite reasonable to preselect energies arbitrarily. In the case of electrons this would not be appropriate since they can lose a major fraction of their energy in a single collision and consequently they may jump over certain energy intervals. Therefore, in the continuous slowing-down approximation a set of predetermined mean energy losses is obtained by defining a sequence of decreasing energies. It is advisable to use a combination of two types of spacing: uniform and logarithmic spacing. In logarithmic spacing the energy E_n in the step n is given as $E_n = kE_i$, where k is a reduction factor and E_i is the initial energy of protons [13]. In general, it is convenient to set the reduction factor $k = 2^{-n/m}$, where m is an integer, so that in the absence of energy loss straggling the proton would lose half of its energy in m steps. The values of m are usually between 8 and 32. Logarithmic spacing has the advantage that angular multiple-scattering deflection per step changes little from step to step. But, it introduces a large number of steps and considerably increases computing time. In the case of uniform spacing the angular deflection increases from step to step. Therefore, uniform spacing is used for higher energies of the energy grid and to limit the angular deflection to the desired small value toward the end of history. Logarithmic spacing is applied for lower energies down to the cut-off energy.

The amount of energy lost by proton on a path-length will not, in general, be equal to the mean energy loss because of the statistical fluctuations which occur in the large variety of discrete collisions suffered and in the energy transferred in each collision. An initially monoenergetic proton beam, after passing through a fixed thickness of matter, will therefore show a distribution in energy. Since the number of proton collisions with electrons is much larger than with nuclei, only the fluctuation of energy loss, *i. e.*, the energy loss straggling, due to ionization is considered. It is most convenient to sample it from the Vavilov's distribution [14]. The distribution of the energy losses according to the theory of Vavilov is:

$$\Phi(\lambda) = \int_{\lambda}^{\infty} \frac{d\lambda}{\pi \varepsilon_{\max}} \exp[\kappa(1+\beta^2\gamma)] \cdot$$

$$\cdot \int_0^{\infty} dy \exp\left[\kappa\left(f_1 - y^2 \frac{D}{\varepsilon_{\max}}\right)\right] \cos(y\lambda + \kappa f_2) \qquad (2)$$

where λ is a scaled energy loss variable related to the energy loss Δ and the mean energy loss $\overline{\Delta}$ according to the following relation:

$$\lambda = \frac{\Delta - \overline{\Delta}}{\xi} + \overline{\lambda} \qquad (3)$$

with

$$\overline{\lambda} = -1 + \gamma - \beta^2 - \ln\kappa \qquad (4)$$

and

$$\xi = 2\pi r_e^2 m_e c^2 \frac{\Delta s}{\beta^2} \sum_j \omega_j \frac{Z_j}{A_j} N_a \qquad (5)$$

The skewness parameter κ, the maximum amount of energy $\varepsilon_{\max}$ which a proton can lose in a collision with an orbital electron (considered as free) and the correction D [15] aimed to include binding effects of atomic electrons are defined as follows:

$$\kappa = \frac{\xi}{\varepsilon_{\max}} \qquad (6)$$

$$\varepsilon_{\max} = \frac{2m_e c^2 \beta^2}{1-\beta^2} \tag{7}$$

and

$$D = \frac{4}{3}\sum_n I_n \frac{Z_n}{Z_j} \ln \frac{2m_e c^2 \beta^2}{I_n} \tag{8}$$

The quantities f_1 and f_2 containing the sine and cosine integrals, $Si(y)$ and $Ci(y)$, are defined as:

$$f_1 = \beta^2[\ln y - Ci(y)] - \cos y - ySi(y) \tag{9}$$

and

$$f_2 = y[\ln y - Ci(y)] + \sin y + \beta^2 Si(y) \tag{10}$$

In these equations r_e is the classical electron radius, $m_e c^2$ the electron rest energy and γ the Euler's constant. Z_j, A_j, N_a and ω_j are the atomic number, Avogadro constant, atomic weight and fraction by weight of the j^{th} atomic constituent, while I_n and Z_n are the effective ionization potential and the electron number of the n^{th} shell. Correction including binding effects of atomic electrons becomes more important for heavier elements tending to widen the distribution of Vavilov. In order for Vavilov's distribution to be accurate two conditions have to be satisfied: the path length has to be long enough so that ξ is much greater than the mean excitation energy of the material and the path length must be short enough so that the mean energy loss $\overline{\Delta}$ is small compared to the initial proton energy. Moreover, for small κ Vavilov's distribution approaches Landau's distribution, while for large κ it approaches a Gaussian distribution. One could say that it is more general than the other two.

There are several multiple-scattering theories, but they all disregard the correlation between deflections and energy losses within each step as well as spatial deflections. Although the theory of Goudsmit and Saunderson [16] has no limitation on the magnitude of the angular deflections, the theory of Molière [17] is easier to apply and thus it is commonly used. The multiple-scattering angular deflection in each step is specified by the polar angle θ and the azimuthal angle φ, in a coordinate system whose polar axis coincides with the direction of the motion of the proton at the beginning of the step. In successive steps the polar angles θ are sampled from the Molière distribution, while the azimuthal angles φ are sampled from a uniform distribution assuming that the medium is isotropic. The distribution of multiple-scattering angular deflections according to Molière is expressed as a function of the reduced scattering angle, *i. e.*, a scaled angular variable, ϑ and is:

$$F(\vartheta) = \int_0^{\vartheta} d\vartheta\, \vartheta C_B \cdot$$

$$\cdot\left[\exp(-\vartheta^2) + \frac{f^{(1)}(\vartheta)}{B} + \frac{f^{(2)}(\vartheta)}{B^2} + \right.$$

$$\left. + \frac{f^{(3)}(\vartheta)}{B^3} + \cdots\right] \tag{11}$$

with

$$\vartheta = \frac{\theta}{\chi_c \sqrt{B}} \tag{12}$$

where χ_c and B are parameters which express the dependence in proton energy and path-length. These parameters are evaluated on the basis of a single-scattering theory developed by Molière which is fairly exact. Molière's multiple-scattering theory was developed by adopting that the path-length is long enough for the occurrence of at least 20 collisions on the average. It also assumes the small-angle approximation and is therefore applicable when the multiple-scattering deflection angles θ are no greater than approximately 20 degrees. Although it is not a significant restriction for protons, still it has been removed and the applicability extended to large angles, through a correction factor $C_B = \sqrt{\sin\theta/\theta}$ [18]. Since no energy loss is built into the theory, a small size of the step is required. The expression in inverse powers of B in Eq. (11) is accurate only when B is larger than about 4.5. The use of more than three terms in this expansion would practically not increase the accuracy because of approximations made elsewhere in derivation of the theory. The expansion coefficients in Eq. (11) contain a Bessel function J_0 and are given by:

$$f^{(n)}(\vartheta) = \frac{1}{n!}\int_0^{\infty} dy \left[\frac{y^2}{4}\ln\frac{y^2}{4}\right] J_0(\vartheta y)\exp\left(-\frac{y^2}{4}\right) \tag{13}$$

Molière's parameter B is obtained solving iteratively the equation:

$$B - \ln B = \ln \Omega_0 + 1 - 2\gamma \tag{14}$$

with

$$\Omega_0 = \left(\frac{\chi_c}{\chi_a}\right)^2 \tag{15}$$

where Ω_0 can be interpreted as the number of collisions in the step, while χ_c is the characteristic angle and χ_a is the screening angle. A detailed analysis of parameters χ_c and χ_a will not be performed here, except that it should be noted that since this theory takes into account only elastic collisions with nuclei and disregards inelastic colli-

sions with atomic electrons, a correction has been introduced into χ_a to take into account the influence of the orbital electrons [19].

As the consequence of the multiple-scattering deflection there is longitudinal and lateral displacement. In a Cartesian coordinate system whose axis coincides with the direction of motion at the beginning of each step, displacements are calculated from the following approximate expressions:

$$\Delta x = \frac{\Delta s_n}{2}\left[\sin\theta\cos\varphi + k_x\sqrt{\frac{\overline{\theta^2}}{6}}\right] \qquad (16)$$

$$\Delta y = \frac{\Delta s_n}{2}\left[\sin\theta\sin\varphi + k_y\sqrt{\frac{\overline{\theta^2}}{6}}\right] \qquad (17)$$

$$\Delta z = \frac{\Delta s_n}{2}(1+\cos\theta) \qquad (18)$$

where k_x and k_y are random variables sampled from a Gaussian distribution, while $\overline{\theta^2}$ is the mean square multiple-scattering deflection which is approximated by $\chi_c^2(B-1.2)$ where χ_c^2 and B are variables in Molière's multiple-scattering theory. When sampling on the bases of these formulas, very large values of k_x and k_y, for which $\Delta x^2+\Delta y^2+\Delta z^2 > \Delta s_n^2$ must be excluded [4].

The transport of energy by secondary electrons emerging from ionization events is usually ignored in proton transport simulation and dosimetry at energies of therapeutic interest. This approximation is quite reasonable due to the low energy of secondary electrons, thus having exceedingly short ranges compared to those of primary protons. Consequently, the transport of energy by secondary electrons has an effect on depth-dose curves only at superficial depths, giving rise to a rapid dose build-up.

In nonelastic nuclear interactions protons are removed from the beam and it is necessary to evaluate the fraction of energy lost by protons that escape in the form of secondary protons, charged particles heavier than protons (deuterons, tritons, alpha particles, *etc.*), uncharged particles (neutrons and photons) and the fraction that can be considered to be absorbed locally. Therefore the spatial transport of energy by secondary particles issued form compound nuclei has to be considered. An approximation of this is to assume that the whole energy of the removed proton is absorbed on the site of the nonelastic nuclear interaction. A more realistic consideration is to adopt that the uncharged particles leave the scoring geometry without any energy deposition, although a part of the energy transferred to the secondary neutrons is delivered in this geometry. Most of the neutrons are emitted with a high energy component in the forward direction and interact far from the proton track, thus having almost no contribution to the depth-dose curve. It is also assumed that the particles heavier than protons deliver their energy on the site of interaction, while the secondary protons are transported further until their energy falls below the transport cut-off energy. The transport cut-off energy is the same for primary and secondary protons and should not exceed a few hundreds keV for therapeutic simulations. The occurrence of a nonelastic nuclear interaction can be sampled via a probability per unit distance [5, 20] which depends on the total cross section for nonelastic nuclear interaction. Another simple approach is to introduce survival weight factors [4], depending also on the mentioned cross section, which represent the probability that the proton has not been absorbed in a step by a nonelastic nuclear reaction. The data for the total reaction cross section can be obtained from calculations using the GNASH nuclear model code [21]. When a proton is absorbed, more than one secondary proton maybe emitted, but also none. Therefore, the mean proton multiplication factor for each incident proton energy is sampled. If the secondary protons are to be further transported, their emission energies and angles are needed. By integrating double differential cross sections cumulative distributions are formed and the required values are sampled by picking a uniformly distributed random number [22].

Simulation of combined proton and secondary electron transport

There are certain cases when the transport of secondary electrons should not be neglected. This concerns simulations at the microscopic level in microdosimetry and in radiobiology where there is an interest in the energy deposition, away from the interaction site, by electrons having low energies. Moreover, electron ranges in air are considerably larger than the size of the cavity of an ionization chamber. Thus, the assumption of energy deposition on the site of secondary electron production can induce inaccuracy in the absorbed dose evaluations.

To be able to include the generation and transport of secondary electrons within the proton transport simulation, another scheme seems to be quite appropriate. Initially, it has been designed for electron Monte Carlo simulations and is based on a mixed procedure [4]. Here collisions with small energy losses and deflections are grouped, but occasionally catastrophic collisions, where the loss or defection are very large, are treated separately by conventional random sampling according to the single-scattering cross sections. This means that individual collisions, which are those where the

energy loss is greater than the value of a preselected energy limit, are excluded from grouping. The particle history is divided into sections, in which no catastrophic collisions occur and where continuous slowing-down is assumed, while the section is terminated by a catastrophic collision. The advantage of this mixed simulation scheme is that the initial state of a secondary knock-on electron is defined unambiguously; there is a direct correlation between the energy lost by the primary proton and the energy transferred to the secondary electron, the emission angle is quite accurately evaluated and correlation between energy loss fluctuations and multiple-scattering defections is represented more reliably. However, the random occurrence of catastrophic collisions leads to less storing of predigested transition probabilities for the random walk, which results in more time-consuming calculations.

In simulation, the size of the step is determined according to the distance between proton-electron collisions in which the proton energy losses are larger than a preselected energy limit, or whenever a nonelastic nuclear interaction occurs, and is sampled during the transport [5, 20]. The type of interaction is determined by random sampling at the end of each step. Below the preselected energy limit energy losses and angular deviations are grouped together and treated as multiple events using continuous slowing-down approximation for energy losses and Molière's multiple-scattering theory for angular deviations. Since only losses below the preselected energy limit are included in the step, restricted collision stopping-powers are used, which can be derived from unrestricted collision stopping-powers given in ICRU 49. To these losses energy losses due to elastic collisions with nuclei are added, evaluated using nuclear stopping-powers from ICRU 49. Above the preselected energy limit single collision events are considered where the proton energy loss is sampled from the Rutherford cross section, providing energy loss straggling between the preselected energy limit and the maximum energy that a proton can lose in one single proton-electron collision. Sampling of step size imposes restrictions on the choice of the preselected energy limit. A large value of the preselected energy limit enables fast calculations, since few single events occur, but gives a poor description of proton energy loss straggling. A low value of the preselected energy limit shortens the step size and increases computation time, but the energy straggling is accurately modelled. It has been found that an appropriate value for the preselected energy limit is 10 keV. In the single collision event, a secondary knock-on electron is created. Its initial energy and direction are determined by the kinematics of the collision and it is further transported according to the continuous slowing-down approximation and the multiple-scattering theory. Secondary protons are treated and transported as described earlier.

CONCLUSION

It is obvious that radiotherapy and especially proton therapy is very efficient in the sterilization of malignant growths, but is also very delicate since healthy tissue surrounding ill tissue should not be affected at all or very little by the proton beam [23, 24, 25]. Therefore accurate treatment planning and dosimetry, as well as beam preparation, are required in proton therapy. However, it seems that the reliability of mentioned codes at therapeutic energies and certain physical processes that are simulated as well as data libraries are still not known with satisfactory certainty [6, 7, 20, 26]. But the importance and role of some effects is clear. Almost all comparisons and analysis have been done for water since it is considered, in general, as a tissue equivalent medium. It has been shown that for therapeutic energies in general the influence on depth-dose distribution of secondary particles created in nonelastic nuclear interaction is rather small. Even for higher energies of the energy range used for therapy (50–250 MeV) the contribution to the total energy deposition from heavy secondary particles is very small, with the exception of secondary protons having a considerable contribution of about 10%, which decreases towards the end of the range. This rather small contribution of heavy secondary particles comes from the fact that the contribution of a nonelastic nuclear interaction to the total probability for an interaction per unit depth is less than 0.1%. At higher energies, in the entrance region of the proton depth-dose curve, discrepancy of about 15% has been observed between simulations when the energy of secondary protons has been absorbed on the sight of their production in nonelastic nuclear interactions and when secondary protons are transported until their energy falls below the cut-off energy. Furthermore, along the plateau part of the curve the discrepancy is inverted and becomes smaller, almost disappearing before the Bragg peak. In fact, there is an overestimation of the absorbed dose in the entrance region when the energy of secondary protons is absorbed locally. This effect is smaller at lower energies. An important influence of nonelastic nuclear interaction on the depth-dose distribution, at higher energies, can be seen when nonelastic nuclear interactions are excluded from the simulation compared to when they are fully taken into account. Nonelastic nuclear reactions remove primary protons from the beam, which leads to the reduction of the peak-to-plateau ratio by about 40%. Again, this effect is smaller at lower energies. It has been shown also that the influence on the depth-dose distribution of secondary electrons is very important, giving almost constant contribution of about 20% to the total absorbed dose at higher energies, while it decreases for lower energies. However, they have very small ranges, but can play a role in dosimetry with ionization chambers.

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Иван ПЕТРОВИЋ

МОНТЕ КАРЛО СИМУЛАЦИЈА ТРАНСПОРТА ПРОТОНА НА ТЕРАПИЈСКИМ ЕНЕРГИЈАМА

Да би се показала потреба за прецизним симулацијама протонског транспорта у терапијским применама анализиране су физичке и биолошке карактеристике протона, као и технички захтеви који се траже од протонског снопа. Упоређени су и описани неки Монте Карло рачунарски програми за симулацију протонског транспорта који се користе на терапијским енергијама. Општи приказ две шеме транспорта протона су изложене; једна која укључује настајање и транспорт секундарних протона и друга која обухвата такође настајање и транспорт секундарних електрона. Заснована на различитим стеченим искуствима извршена је анализа и улоге секундарних честица.

Кључне речи: Монте Карло симулација, протонски транспортни кодови, карактеристике протона, секундарних честица, терапијске енергије, дозиметрија, биомедицинске примене протона