The role of nuclear reactions in Monte Carlo calculations of absorbed and biological effective dose distributions in hadron therapy

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Abstract

Monte Carlo codes are rapidly spreading among hadron therapy community due to their sophisticated nuclear/electromagnetic models which allow an improved description of the complex mixed radiation field produced by nuclear reactions in therapeutic irradiation.
In this contribution results obtained with the Monte Carlo code FLUKA are presented focusing on the production of secondary fragments in carbon ion interaction with water and on CT-based calculations of absorbed and biological effective dose for typical clinical situations. The results of the simulations are compared with the available experimental data and with the predictions of the GSI analytical treatment planning code TRiP.

1 Introduction

The use of ion beams in tumour therapy requires accurate understanding and description of the complex process of ion interaction with matter, especially regarding the production of secondary particles. In fact, during radiation therapy, secondary neutrons, protons and heavier fragments contribute to the dose delivered to the tumour and healthy tissue outside the treated volume. Production of light fragments is of special interest since these particles going through the patient body broaden the irradiation field and increase the risk of secondary tumours in healthy tissue. In addition, the secondary particles leaving the patient body could be exploited for in-vivo verification of the treatment delivery simultaneously to the therapeutic irradiation. Furthermore, the biological efficacy of the reaction products differs from that of the primary ions and has to be included in biological dose calculations for a correct treatment planning.

Monte Carlo (MC) statistical methods are increasingly considered powerful computational tools for accurate calculations of dose deposition in treatment planning, since they are assumed to provide a realistic representation of the physical interactions undergone by the primary and the secondary ions which are produced. Among the existing MC codes, FLUKA [1,2] represents a valuable choice thanks to:

- Its precise and reliable physical models for transport and interaction of all the components of the expected radiation field;
- The capability to import the irradiation geometry from CT scans to carefully take into account the density and the composition of the irradiated areas [3-5];
- The coupling to radiobiological models for the evaluation of biological effects, like cell killing [5-7].

In this contribution, we present results from a recent benchmark of the FLUKA code against mixed field measurements for a 400 MeV/u carbon ion beam on water targets [5,8,9] as well as calculations

of physical and biological dose deposition for carbon ion beams in the patient anatomy as given by the diagnostic CT (Computed Tomography) scan [5,6]. These latter calculations have been compared with the predictions of the GSI analytical treatment planning (TRiP98, TReatment Planning for Particles, 1998) [10-12].

2 Material and Methods

During therapeutic irradiation nuclear reactions occur between the incident ions and the target tissue. These processes need to be correctly taken into account for estimating how the radiation field is modified through a decrease of the primary ion yield and a build-up of secondary fragments. In particular secondary lower-charge fragments, having longer ranges than primary ions, produce a characteristic dose tail beyond the Bragg peak. Their angular and energy spectra also substantially differ from that of the primary ions. Light fragments, such as protons and alpha particles, have a broad angular distribution while heavier fragments are emitted in a rather narrow cone around the primary beam track.

Promising initial benchmarks of FLUKA against models and experimental data were already reported in [13] for therapeutically relevant ion beams. Recently, new experimental measurements have been performed at GSI to investigate and characterize the more complex mixed radiation field produced by a carbon ion beam at 400 MeV/u (i.e., corresponding to a very deep seated tumor) impinging on water targets of various thickness [8,9]. Therefore, these new experimental measurements have been simulated with the new development version of the FLUKA code interfaced with the latest version of the BME (Boltzmann Master Equation) event generator [14].

For calculating biological optimized patient plans Treatment Planning Systems (TPS) for carbon ion therapy have to deal with the complexity of the mixed radiation field. Differently from proton therapy where typically a constant relative biological effectiveness (RBE) of 1.1 is used, the physical beam models of carbon ion TPS in order to correctly estimate their RBE have to take into account the secondary fragment yield at each penetration depth in terms of ion species and energy. In clinical practice, TPS for hadron therapy are essentially analytical codes based on fast performing pencil-beam algorithms and on input physical databases describing the electromagnetic/nuclear interaction of the incoming beam in water.

However, MC codes are being more and more considered valuable computational tools to support treatment planning, due to their accurate estimation of the mixed radiation field in arbitrary materials. In fact, they allow dose evaluation taking into account the realistic patient stoichiometry and anatomy instead of the water-equivalent approach typically exploited by the analytical treatment planning algorithms [3-5]. This can be particularly advantageous in the description of the projectile/target fragmentation, and in the presence of large density gradients. Finally, MC simulations can provide accurate physical databases for TPS [15].

In order to perform biological effective dose calculations, FLUKA has been interfaced with the Local Effect Model (LEM) [16-18] that has been successfully applied within treatment planning in the GSI Helmholtzzentrum für Schwerionenforschung pilot project for carbon ion tumour therapy over more than 10 years. This model is based on the knowledge of charged particle track structure in combination with the response of biological objects to conventional photon radiation. Starting from the LEM generated relative biological effectiveness tables we calculated on a particle by particle basis the biological response after carbon ion irradiation following the *low dose approximation* approach [18]. This approach has been tested simulating carbon ion pristine Bragg peaks [5] and *patient-like* superimposition of opposed therapeutic ^{12}C ion fields [6] in water as well as patient plans in the CT system [6,7].

3 Results and Discussion

Examples of the results obtained for the benchmarking of FLUKA against experimental data for a 400 MeV/u carbon ion beam in water are reported in figures 1 to 4 [5,8,9]. Figure 1 depicts the depth-dose curve in water, split into the contribution from the primary beam and the secondary fragments [19], while the figure 2 shows the simulated contribution of the individual secondary fragments. The tail consists mainly of H and He fragments but a not negligible contribution is due to heavier fragments such as B (figure 2). Its correct estimation is demanded for a reliable determination of the dose delivered to the healthy tissues in the proximity of the treated tumour.

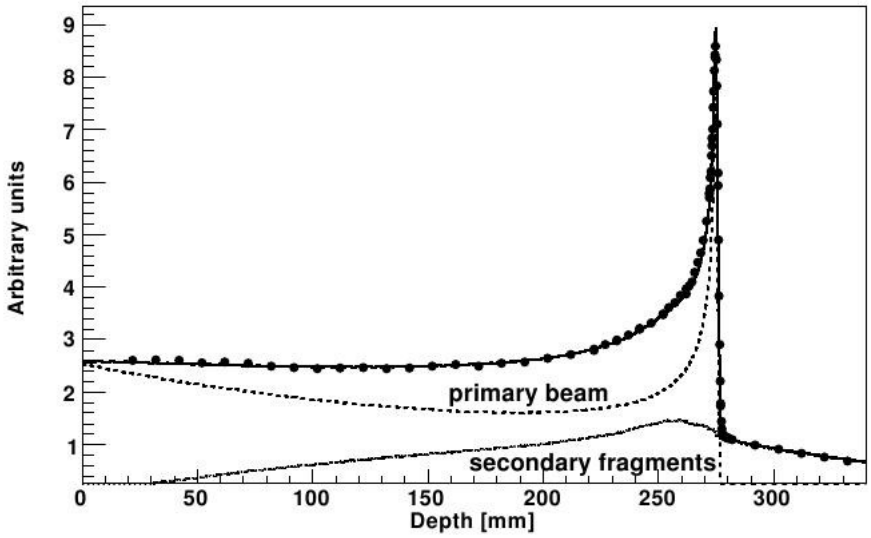

Figure 1: Bragg curve as a function of depth in water for a 400 MeV/u carbon beam. The points [8,9] and the solid line [19] represent the experimental data and the FLUKA calculations, respectively. The dose contribution from primary ^{12}C ions and secondary fragments is also reported. Both the experimental data and the MC results are normalized to give the same integral dose between the entrance region and the Bragg peak.

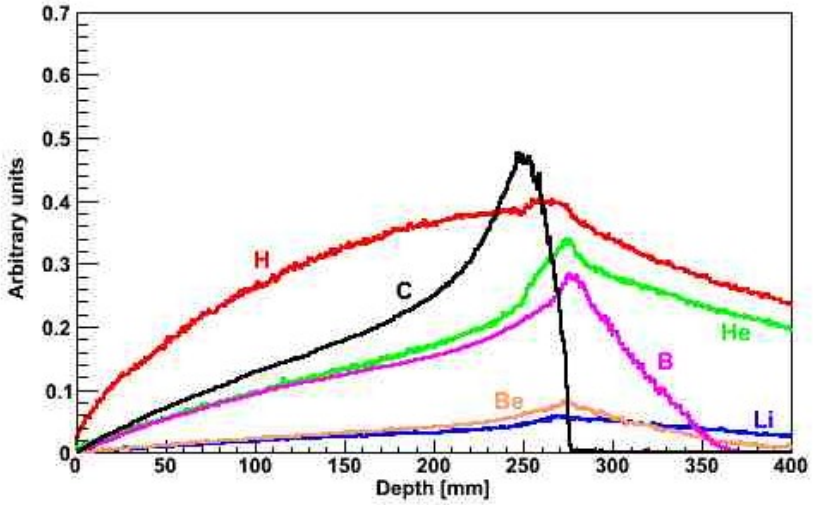

Figure 2: Simulated contributions of the indicated secondary particles to the Bragg curve shown in figure 1.

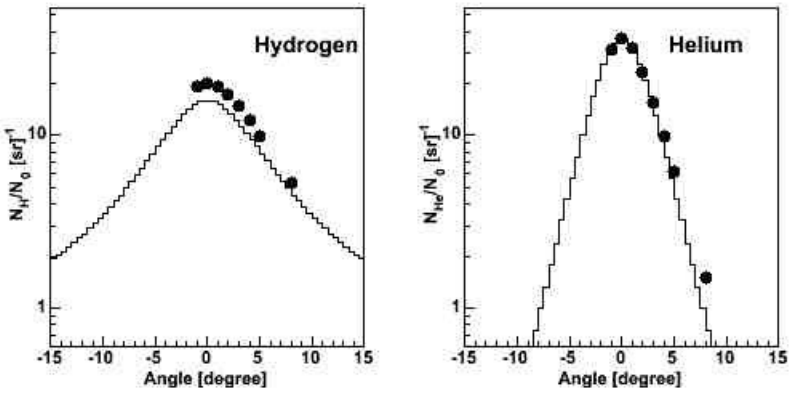

Figure 3: Angular distributions of the light secondary fragments (H and He) behind a 31.2 cm thick water phantom irradiated with a 400 Me/u carbon ion beam. The points [8,9] give the experimental data while the histograms depict the FLUKA results [5].

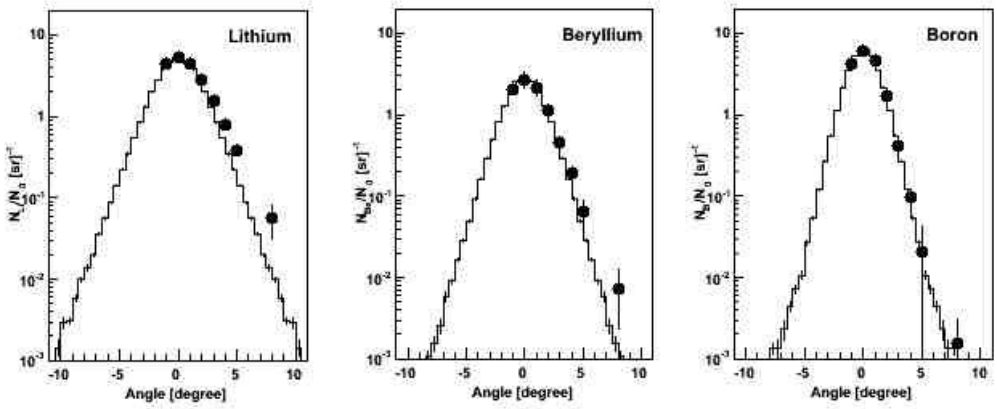

Figure 4: Angular distributions of the heavy secondary fragments (Li, Be and B) behind a 31.2 cm thick water phantom irradiated with a 400 MeV/u carbon beam. The points [8,9] give the experimental data while the histograms depict the FLUKA results [5].

Figure 3 and figure 4 show the angular distributions of the secondary products behind a 31.2 cm thick water phantom still in 400 MeV/u ^{12}C irradiation. Generally, the width of the angular distribution depends on the fragments; He and especially H have broad distributions. With increasing mass, the distributions become progressively narrower. At this depth the fragment spectrum is dominated by H and He fragments while the amount of boron drops rapidly. The lighter fragments show the broadest angular spectra while the heavier ones (Li, Be and B) are emitted in a rather low narrow cone of about 0° to 5°. The Monte Carlo simulations reproduce all these features except for H where an underestimation of its yield is evident in the very forward direction. This discrepancy suggests the necessity of further ameliorations both in the nucleus-nucleus event generators and in the transport algorithms to cope with the large number of effects to be considered for simulating a thick target experiment. Among them, the accurate modelling of the experimental setup could be especially important. However, the shown results, in addition to what already presented in [5,13] seem to indicate that FLUKA reliably describes the angular distribution of the mixed radiation field. This is an important aspect in order to estimate the broadening of the irradiation field in therapy applications.

Figure 5 represents a comparison between FLUKA calculated dose deposition and the planned treatment obtained with TRiP98 [10-12] for a clivus chordoma patient treated at GSI with carbon ion beams [6]. The shapes of the calculated dose distributions are found in good agreement except in the peripheral low dose region probably due to the fact that MC fully takes into the account multiple scattering of primary beam and angular yield of secondary fragments whereas this version of TRiP98 does not. However, in this specific patient case this simplification of the analytical treatment planning system has no clinical impact. By interfacing the LEM model with FLUKA we have additionally calculated the biological effective dose distributions. An example of the obtained results is reported on the right side of figure 5 for the same patient case depicted on the left side.

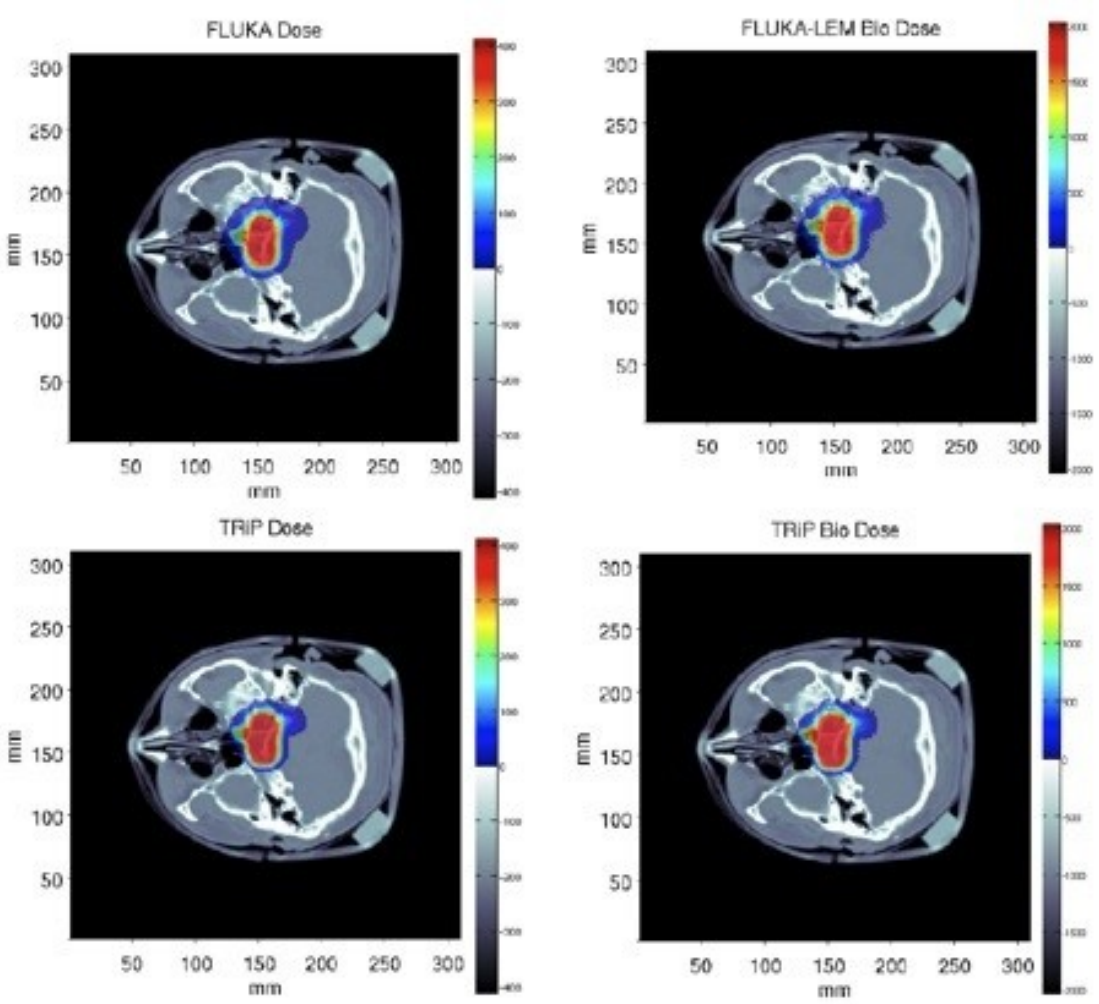

Figure 5: MC versus TRiP98 calculated distributions of absorbed dose (left side) and biological dose (right side) for a clivus chordoma patient. The rainbow colour-bar displays absorbed/biological dose values. The black-white bar represents the Hounsfield unit map arbitrarily rescaled for display purposes.

4 Conclusions and Outlook

As a result of the recent efforts made by the FLUKA Collaboration to produce reliable nucleus-nucleus event generators in the energy range of therapeutic relevance, the FLUKA Monte Carlo code now represents a valuable tool for all the ion species selected for the operational and upcoming ion treatment facilities in the entire energy range of therapeutic relevance.

Besides physical dose calculations in standard geometries and directly on the patient CT scan, the novel interface with LEM [6,7] allows one to perform with FLUKA also biological effective dose calculations in carbon ion therapy, as actually made with the biological models used by the currently available analytical TPS.

Although the long computing time prevents, at the moment, the use of the FLUKA code both for proton and carbon ion calculations in daily clinical routine, Monte Carlo methods can be vey useful for deeper investigations of recalculated treatment plans in selected patient cases. Intercomparisons between analytical TPS and MC forward recalculations for critical clinical situations in the presence of metallic implants and large tissue inhomogeneities are ongoing at the HIT facility.

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