Novel imaging and quality assurance techniques for ion beam therapy: a Monte Carlo study

I. Rinaldi[1], A. Ferrari[2], O. Jäkel[1,3], A. Mairani[3,4], K. Parodi[3]
[1]German Cancer Research Center, Heidelberg, Germany, [2]CERN, Geneva, Switzerland, [3]Heidelberg Ion Therapy Center, Heidelberg, Germany, [4]INFN Section of Milan, Milan, Italy

Abstract
Ion beams exhibit a finite and well defined range in matter together with an "inverted" depth-dose profile, the so-called Bragg peak. These favourable physical properties may enable superior tumour-dose conformality for high precision radiation therapy. On the other hand, they introduce the issue of sensitivity to range uncertainties in ion beam therapy. Although these uncertainties are typically taken into account when planning the treatment, correct delivery of the intended ion beam range has to be assured to prevent undesired underdosage of the tumour or overdosage of critical structures outside the target volume. Therefore, it is necessary to define dedicated Quality Assurance procedures to enable in-vivo range verification before or during therapeutic irradiation. For these purposes, Monte Carlo transport codes are very useful tools to support the development of novel imaging modalities for ion beam therapy. In the present work, we present calculations performed with the FLUKA Monte Carlo code and preliminary experimental studies.

1 Introduction

Ion beam therapy has no primary radiation emerging from the patient, in fact the energy deposited by a therapeutic ion beam increases in front of the tumor target and sharply decreases in the healthy behind the target, where no or small amount of dose is deposited. This "inverted" depth-dose profile, the so-called Bragg peak, represents a major advantage of ion beams over conventional external beam modalities for highly conformal dose delivery. On the other hand, the finite range of the beam in the patient needs to be accurately determined for correct dose deposition to the target volume. Therefore, in-vivo verification of the actual treatment delivery requires dedicated Quality Assurance (QA) and novel imaging techniques for in-vivo monitoring of the ion beam range and/or reliable indicators of the ion dose deposition. Dose calculations and optimization in particle treatment planning are tipically computed on X-ray CT images, which represent the distribution of mean X-ray absorption coefficients relative to water. From X-ray CT data the particle ranges in tissue can be calculated only with about 1-3% range accuracy [1, 2], corresponding to few millimeters in some clinical cases. The main limiting factor is the translation of the Hounsfield units, as measured with a CT scanner, to water equivalent path length (WEPL). This translation, which is presently based on semiempirical calibration curves [2, 3], can cause differences between treatment planning and treatment delivery. One straightforward way to avoid this uncertainty and to improve the accuracy of the calculated particle ranges in tissue could be the use of ion radiography or tomography [4, 5]. This requires the usage of high energy primary particles for obtaining low dose transmitted planar (radiographic) or volumetric (tomographic) images of the patient for pre-treatment verification of the residual ion range. In addition, this method can allow obtaining information on the correct positioning of the patient without the use of external X-ray radiation. Besides, detection of the emerging secondary particles from the primary ion beam could be exploited for in-vivo verification of the treatment delivery simultaneously to the therapeutic irradiation.

2 Material and Methods

In order to study the feasibility and optimal detection systems for new QA and imaging techniques, Monte Carlo (MC) codes are useful tools to simulate the complex processes of the ion interactions with matter, especially regarding the production of secondary particles. In this work, the calculations were performed using the FLUKA MC code.

FLUKA [6, 7] is a general purpose Monte Carlo code for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy and others. At energies above 100 MeV/n the event generator Relativistic Quantum Molecular Dynamics (RQMD) [8] is used to model nuclear interactions. Nuclear interactions of ions below 100 MeV/u are handled by the Boltzmann Master Equation (BME) [9] event generator which is still under development but available under request.

2.1 Validation of FLUKA nuclear and electromagnetic models

For carbon and heavier ions, the FLUKA nuclear and electromagnetic interaction models have been validated against experimental data in the whole energy range of relevance for therapy already in [10-13]. An example is shown in Fig. 1.

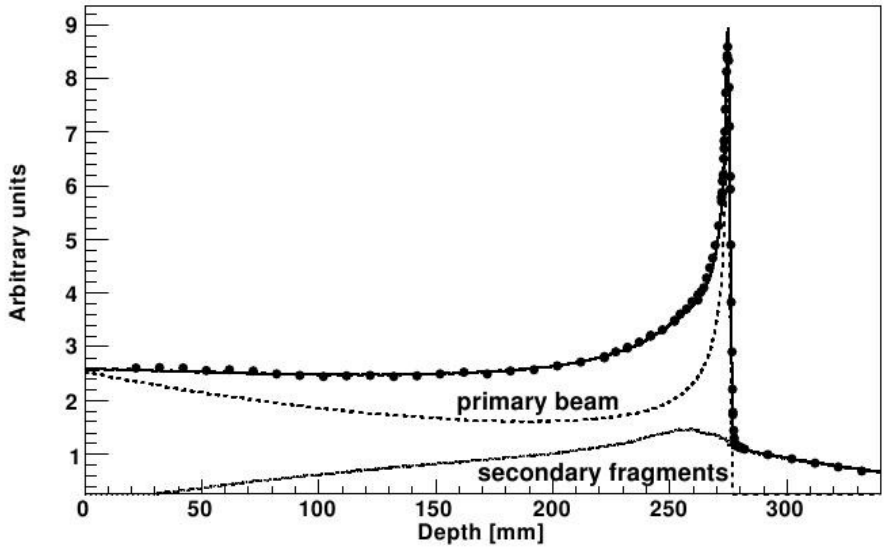

Fig. 1: Bragg curve as a function of depth in water for a 400 MeV/u carbon beam. The points [14] and the solid line [11] represent the experimental data and the FLUKA calculations, respectively. The dose contribution from primary ^{12}C ions and secondary fragments is also reported. Both the experimental data and the MC results are normalized by the integralo f the Bragg curve calculated between the entrance region and the Bragg peak because the experimental data are obtained as relative values.

Promising comparisons of FLUKA calculations and experimental data for dosimetric and radiobiological applications of proton beams were already reported in [15, 16]. In this work a Multi Layer Faraday Cup (MLFC) was used for more detailed testing of the relevant interaction models in proton therapy. The MLFC is a detector consisting of sheets of two different materials: insulator and collector. The MLFC detects only the charge, not dose, of the impinging beam. The longitudinal charge distribution along the beam penetration exhibits two distinct regions: a build-up entirely due to nuclear reactions and a sharp peak due to primaries stopping by electromagnetic interaction. Thus, this method enables a sound separation of the two different interaction processes which are responsible for the secondary particle emission and the finite primary ion range, respectively. Previous studies [17,

18] were performed to test GEANT3 and GEANT4 nuclear models for 160 MeV protons stopping in CH_2 (sheets made of polyethylene and brass) and Cu (sheets made of copper and capton). We simulated those two experiments with the FLUKA code. The geometry consists of 66 collector sheets separated by insulator, the active channels are 64 connected to current integrators, while the collector 65 is grounded.

2.2 Ongoing investigation on novel imaging techniques for ion beam therapy

MC calculations are being currently carried out to investigate the feasibility and to compare the performances of particle-based radiographic or tomographic transmission as well as emission imaging techniques. The aim of this ongoing work is to identify alternative or complementary methods to Positron-Emission-Tomography [19] for possible future application at HIT (Heidelberg Ion Therapy Center).

These novel imaging techiques could be performed using:

- transmitted high energy primary particles for low dose 2D and 3D imaging to evaluate the correct patient positioning and verify the ion range before treatment
- emerging secondaries [20, 21], in particular protons, from the therapeutic beams to verify simultaneously and in-vivo the treatment delivery

This contribution presents the preliminary results of the Heavy Ion Computed Tomography (HICT). In the HICT [22, 23] the distribution of the electron density can be derived directly from the Bethe-Bloch formula, measuring the energy or the range loss of the primary beam. This method implies that a small flux of ions of higher energy than that used for therapy, is given to the patient before treatment, so that the exit energy could be measured. In a first step, we studied the clinical potential of the HICT starting from CT data of patients that were treated with carbon ions at GSI (Darmstadt, Germany) during the pilot project. We performed the calculations for the WEPL and beam energies needed to achieve the HICT for head, prostate and sacral cases, using an own-written MATLAB routine. In addition, the MC feasibility of this technique was investigated via MC calculations and compared with the first experimental data acquired using standard radiographic films at HIT on the 1st of June 2009.

The MC feasibility and the measurements for HICT were performed using:

- ^{12}C monoenergetic fields (20×3 cm^2) of 400 MeV/u
- a simple and symmetric PMMA phantom (R = 8 cm) with 5 rods (1 of PMMA, 2 of Air, 1 of Lung and 1 of Cortical Bone, r = 1.4 cm)
- the projections for every 5° from 0° to 180° of the energy loss by ^{12}C ions in the MC simulations and the profiles for every 7.5° from 0° to 180° of relative dose on the films
- a very simple MATLAB-based backprojection algorithm for reconstruction

3 Results and Discussion

3.1 Validation of FLUKA nuclear and electromagnetic models

An example of the validation of the FLUKA nuclear and electromagnetic models against experimental data for proton beam using a CH_2 MLFC is shown in Fig. 2. A more detailed comparison and discussion of the results will be soon reported in a separate paper. In general, from the results obtained in this work and the previous benchmarks of other groups we can state that the FLUKA code achieves promising and reliable results compared to experimental data for its nuclear and electomagnetic models for both protons and carbon ions in the entire energy range of therapeutic interest.

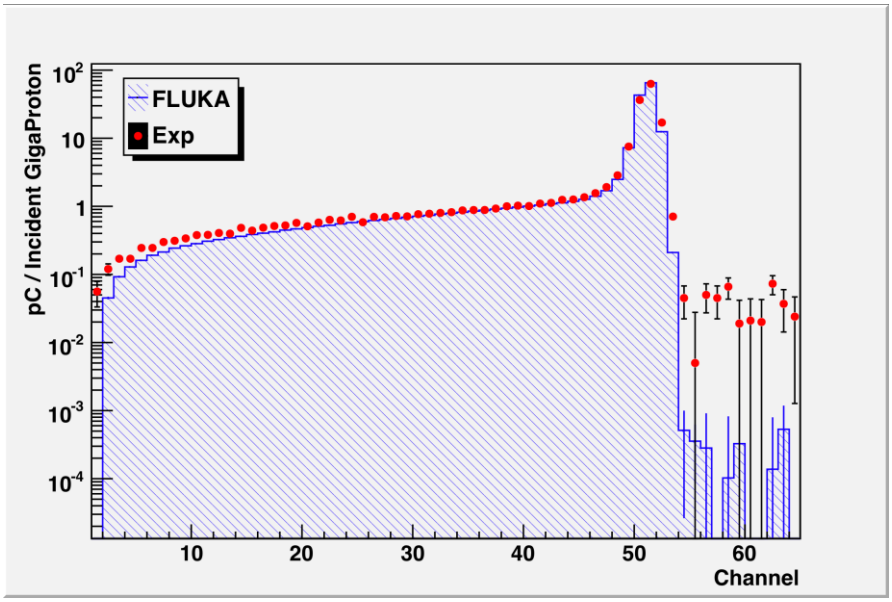

Fig. 2: Experiment (circles) and FLUKA MC calculations (lines) in a logarithmic scale

3.2 Ongoing investigation on novel imaging techniques for ion beam therapy

Regarding the carbon ion beam energies calculated to evaluate the clinical potential of the HICT for head cases we can conclude that the energy values are in a range between 250 and 400 MeV/u, Fig. 3 (left). So, using the HIT accelerator, that is able to accelerate carbon ions until 430.10 MeV/u, it could be possible to performe the HICT for head cases. For the prostate and sacral cases the situation is a little bit more complicated. In fact, carbon ion beams of up to 500 MeV/u are needed for the lateral beam directions which are normally used for treatment, due to the high density bone structure in the beam path. However, it is possible to decrease the energy values by roughly 100 MeV/u via a proper reduction of the beam projections trying to skip the bone structures, for example avoiding beam angles in the [0°, 25°] interval. An example for a feasible projection with an inclination of 30° is depicted in Fig. 3 (right).

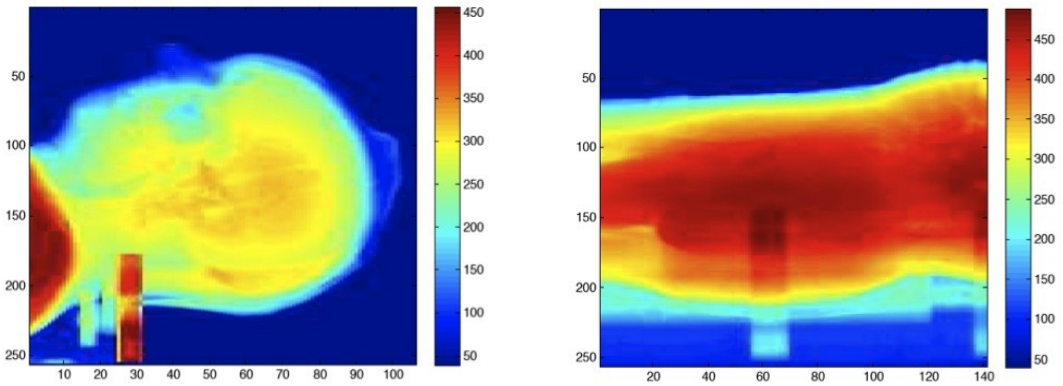

Fig. 3: Carbon ion beam energies, displayed in MeV/u in the rainbow color bars, needed to perform HICT for head (left) and prostate (right) cases

The MC studies for the HICT qualitatively support the feasibility of this method This is shown in the left panel of Fig. 4, indicating that the four rods of different material can be clearly distinguished The results of the first experiment are shown in the right panel of Fig. 4. With this simple approach using standard radiographic films we could only measure relative dose (no energy or range loss) without the discrimination of primary and secondary particles which was performed in the MC calculation. Taking into account the known limitations of the films as detection system for HICT, as well as the discussed

differences between the simulated and experimental quantitities, the reported preliminary results are very encouraging and support our current effort for forthcoming experimental investigations with a better detection system.

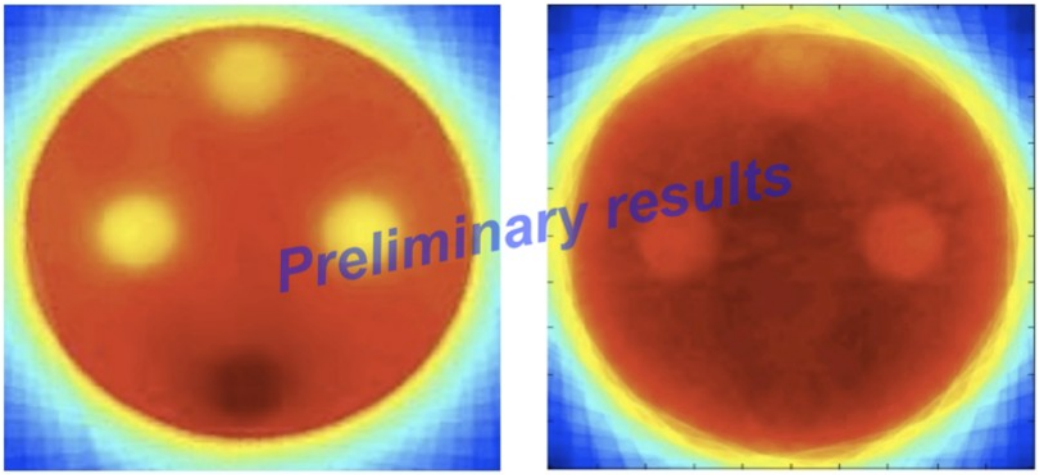

Fig. 4: Qualitative comparison of reconstructed images between MC calculation (left) and measurements (right)

4 Conclusions and Outlook

Previous works for heavier ions and this further investigation for protons support the reliability of the FLUKA nuclear and electromagnetic interaction models for ion therapy applications. In particular, the reported results for the MLFC detector indicate improvements of the nuclear models of the current standalone FLUKA code version with respect to the old FLUKA-based nuclear models implemented in GEANT3 [17]. In addition, the presented MC calculations suggest the feasibility of the HICT if properly selecting energy loss deposition of the primary beam and the first preliminary experimental investigations simply using standard radiographic films are very encouraging. As a next step, MC activities are currently being performed to identify and optimize a more suitable detector system for particle radiography and tomography, as well as to address the feasibility of novel in-vivo range verification techniques via imaging of prompt particle emission during ion irradiation.

Acknowledgement

We thanks Harald Paganetti from MGH Boston for the MLFC experimental data, the FLUKA team for support on the code, the HIT team for the daily discussions and advices and Thomas Haberer for the experimental beam time.

References

[1] B. Schaffner et al, Phys. Med. Biol. 43, 1579-1592, (1998)

[2] O. Geiß et al, GSI Scientific Report 1997

[3] O. Jäkel et al, Med. Phys. 28, 701-703, (2001)

[4] H. Shinoda et al, Phys. Med. Biol. 51, 4073-4081, (2006)

[5] Y. Ohno et al, Nuclear Instruments and Methods in Physics Research A 525, 279-283, (2004)

[6] G. Battistoni et al, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)

[7] A. Fassò et al, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
[8] H. Sorge et al, Nucl. Phys. A 498, 567c, (1989)
[9] F. Cerutti et al, Ricerca Scientifica e Educazione Permanente, Suppl 126, 507, (2006)
[10] F. Sommerer et al, Phys. Med. Biol. 51, 4385-4398, (2006)
[11] A. Mairani et al, Nuovo Cimento C 31, 69-75, (2008)
[12] A. Mairani et al, contribution to this conference
[13] A. Mairani, PhD Thesis, University of Pavia (2007)
[14] E. Haettner et al, Rad. Prot. Dos., 122, 485, (2006)
[15] M. Biaggi et al, Nucl. Instrum. Methods B 159, 89-100, (1999)
[16] K. Parodi et al, Med. Phys. 34, 419-435, (2007)
[17] H. Paganetti et al, Med. Phys. 30 (7), 1926-1931, (2003)
[18] B. Gottschalk et al, Med. Phys. 26, 2597-2601, (1999)
[19] W. Enghardt et al, Nucl. Instrum. Meth. A 525, 284-288, (2004)
[20] C.H. Min et al, Nucl. Instrum. Meth. A 580, 562, (2007)
[21] E. Testa et al, Appl. Phys. Lett. 93, 093506, (2008)
[22] Y. Ohno et al, Nucl. Instrum. Meth. A 525, 279-283, (2004)
[23] H. Shinoda et al, Phys. Med. Biol. 51, 4073-4081, (2006)