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Development and application of tools for Monte Carlo based simulations in a particle beam radiotherapy facility

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HIGHLIGHTS

- Tools for MC-based studies at ion beam therapy facility.
- Effect of dose delivery uncertainties on dose distributions.
- Effect of range uncertainties on dose distributions.

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ABSTRACT

The integration of Monte Carlo (MC) transport codes into a particle therapy facility could be more easily achieved thanks to dedicated software tools. MC approach has been applied to several purposes at CNAO (Centro Nazionale di Adroterapia Oncologica), such as database generation for the treatment planning system, quality assurance calculations and biologically related simulations. In this paper we describe another application of the MC code and its tools by analyzing the impact of the dose delivery and range uncertainties on patient dose distributions.

1. Introduction

The worldwide interest in particle therapy, as demonstrated by the increasing number of hospital-based facilities, is related to the favorable properties of charged particle treatments (Rossi, 2006) in the delivery of highly conformal dose to the target volume while sparing the healthy tissues and organs at risk (OAR). Treatment planning systems (TPSs) are needed to delineate volumes (targets and OAR) and choose and design irradiation parameters (energy, fluences) and geometry. Current commercial TPSs are based on analytical codes performing fast pencil-beam dose calculations (Krämer and Durante, 2010). Monte Carlo (MC) transport codes could provide a powerful tool for accurate dose calculations. While analytical codes are based on a water-equivalent approach, MC methods model the dose deposition process with good accuracy, particularly in heterogeneous material, by handling the real composition of the human body provided by computed tomography (CT) scan (Parodi et al., 2009). This work describes the use of the FLUKA MC code (Ferrari et al., 2005; Battistoni et al., 2007) and the developments of dedicated tools at CNAO, a hospital-based particle therapy facility, to study the dose delivery and range uncertainties effects on patient dose distributions.

2. Materials and methods

2.1. Treatment planning system

The Syngo® VB10 RT Planning (Siemens Medical Solution, Germany) is the commercial TPS used at CNAO. The TPS allows delineating volumes on anatomical images provided by the CT-scanner, which, if needed, can be fused with magnetic resonance images. Then, by defining the number of fields and treatment geometries and applying dose constraints on OAR and targets, it performs an inverse planning optimization, giving as a result the beam irradiation sequence. Energy, position and fluence of each spot are defined in the irradiation beam sequence. The TPS calculates the dose distribution in a patient, handling the patient anatomy with a water-equivalent path length approach. A dose delivery system (DDS) ensures the execution of the irradiation accordingly to the treatment plan irradiation sequence, and the

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position and fluence for each spot are measured and recorded thanks to a redundant system of strip and integral ionization chambers. The TPS allows exporting DICOM files, containing all the information about the patient anatomy, irradiation geometries and beam irradiation sequences.

2.2. FLUKA Monte Carlo code

The MC code used at CNAO is FLUKA (Ferrari et al., 2005; Battistoni et al., 2007). Depth-dose distributions, for both proton and carbon ion beams, have been generated with FLUKA and are used as a dosimetric database for the TPS. MC statistical methods provide accurate dose calculations by modeling more realistically the physical processes (energy loss, straggling, multiple Coulomb scattering of primary beam and secondary fragments and nuclear interactions) and the beam lines geometry. In order to perform a MC simulation, several files derived from the TPS, describing the beam irradiation conditions, are needed.

2.3. In house-made software

In order to generate all the input files needed to perform FLUKA MC simulations (anatomy and beam irradiation geometry information, beam sequences, etc.), an in house-made software was developed at CNAO as a package of tools for FLUKA. It allows converting the DICOM files, output of the TPS into input files for FLUKA. A specific package allows also comparison of dose distributions resulting from the TPS and MC calculations. The comparisons could be made in different ways: using a qualitative approach, i.e. the direct visualization of two dimensional dose distributions, fused with their corresponding CT-scan on axial, sagittal and coronal planes, or by means of dose profiles comparison along the three coordinate axes. For quantitative analysis, dose volume and gamma-index volume histograms are calculated. Another part of the software provides a tool able to generate a new input for the MC from the irradiation records. Using the DDS measurements, giving for each spot the number of particles delivered and their position (horizontal and vertical position), a new input file is generated for FLUKA and a simulation including these measured parameters can be performed. An additional tool gives the possibility to analyze for a whole set of different beam irradiations, made at different times, the evolution of the deviations in position and fluence of each spot compared with the ones planned by the TPS. In order to take into account the uncertainties deriving from CT image acquisition, a dedicated tool allows also simulating the error in the calibration of the Hounsfield units (HUs). This latter acts on the CT gray level miming a possible error of the scanner.

3. Results and discussions

3.1. Dose delivery uncertainty

In order to investigate the impact of dose distribution uncertainties on the patient treatment, comparisons can be made between two dose distributions calculated either with the TPS ion beam sequence or the one recorded from the monitors of the DDS. Before any MC calculations, a first comparison has been made for patient single beam port shown in Fig. 1 in terms of position and fluence deviation between a set of 10 different beam irradiations records for different days of treatment, and the planned ion beam sequence. The mean relative variation of the fluence is 0.05% with a standard deviation of 0.42%, with less than

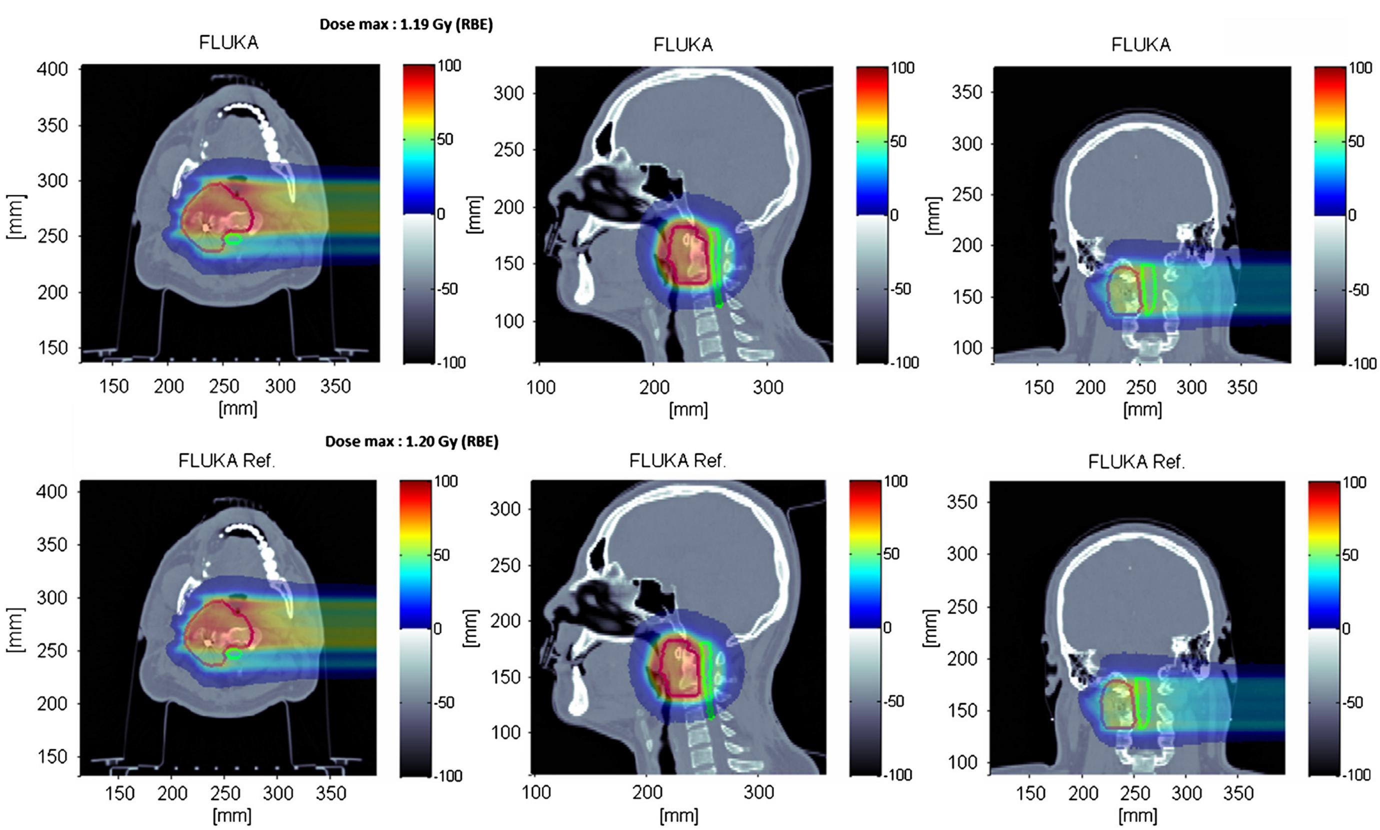

Fig. 1. Comparison of two dose distributions calculated with the planned pencil beam positions/fluence or the recorded ones for one proton beam port. FLUKA ref. (lower panels) refers to the dose distributions (axial, sagittal and coronal views) calculated with the information of the TPS plan. FLUKA (upper panels) refers to the calculation made with the ion beam sequence provided by the monitors of the DDS. The solid lines mark the PTV (planned target volume) and the OAR.