A MONTE CARLO-BASED TREATMENT PLANNING TOOL FOR PROTON THERAPY*

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In the present work, a newly-developed MC-based treatment planning (MCTP) tool for proton therapy is proposed to support treatment planning studies and research applications. It allows for single-field and simultaneous multiple-fields optimization in realistic treatment scenarios and is based on the MC code FLUKA. Relative biological effectiveness (RBE)-weighted dose is optimized either with the common approach using a constant RBE of 1.1 or using a variable RBE according to radiobiological input tables. An example of treatment plan in a patient-CT geometry is presented for clinical treatment parameters as used at the Italian National Center for Oncological Hadron Therapy (CNAO).

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1. Introduction

In this paper, we summarize the results of a new Monte Carlo (MC) based treatment planning (MCTP) tool. It has been initially developed for proton therapy using scanned pencil beams (PB) as applied at the Italian National Center for Oncological Hadron Therapy (CNAO) [1]. First results and details can be found in [2]. The MCTP tools allow to benefit from the superior accuracy of MC calculations with respect to analytic dose engines, especially in difficult and non-standard treatment situations involving large density and tissue heterogeneities or metallic implants [3, 4]. Furthermore, MC particle transport codes allow for the prediction and propagation of emerging secondary radiation, such as β^+-emitters and prompt photons. Prediction of such radiation is of fundamental importance in emerging areas of research aiming at treatment *in vivo* verification.

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Inverse optimization of single field and simultaneous multiple-fields optimization (often referred to as intensity-modulated particle therapy, IMPT) can be performed in water phantoms and patient-CT geometries for different planning target volumes (PTV). Final dose and particle fluency predictions are obtained with the FLUKA MC code [6, 7], used already extensively in hadron therapy applications. As far as the radiobiological part is concerned, a generic Relative Biological Effectiveness (RBE) value of 1.1 can be used [8], which is in accordance with recommendations by the International Commission on Radiation Units and Measurements [9]. Alternatively, values of non-constant RBE are obtained by a re-implementation of the Local Effect Model (LEM, version IV) [10] developed at the Heidelberg Ion-Beam Therapy Center (HIT). In the proposed approach, radiobiological input tables computed with the LEM are interfaced with FLUKA to calculate RBE-weighted doses D_{RBE} [11].

The procedure for performing MCTP calculations of D_{RBE} distributions is described in Sec. 2. In Sec. 3, we briefly summarize the results for patient cases planned my means of MCTP with two and three beam ports. They are compared with commercial TPS calculations.

2. The MCTP workflow

The optimized absorbed dose (D_{abs}) or RBE-weighted dose (D_{RBE}) distributions and the corresponding pencil beam particle numbers $\boldsymbol{N}_2$ are obtained in phantoms or patient CTs in a multi-step procedure, as summarized in Fig. 1.

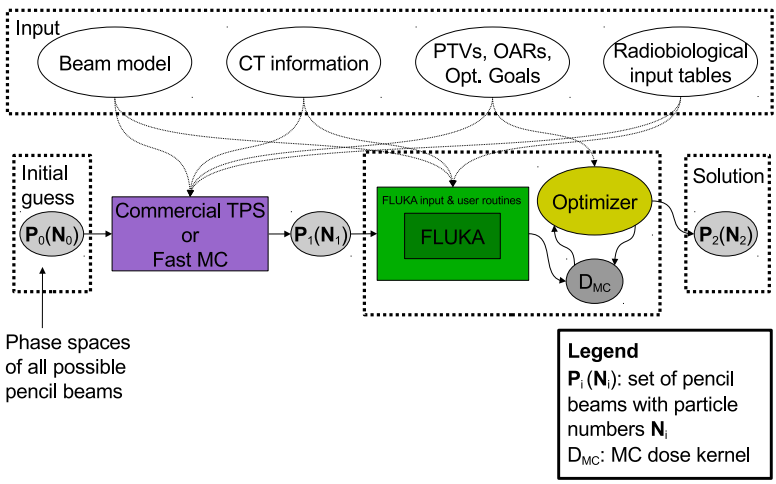

Fig. 1. Components and workflow of the multi-step procedure for dose calculation and optimization.

From a given set of pencil beams $\boldsymbol{P}_1(\boldsymbol{N}_1)$ with pre-optimized initial particle numbers $\boldsymbol{N}_1$, a MC-optimized solution $\boldsymbol{P}_2(\boldsymbol{N}_2)$ is obtained iteratively using a FLUKA-calculated dose kernel D_{MC}. To obtain an adequate set of pencil beams $\boldsymbol{P}_1$ and an initial guess $\boldsymbol{N}_1$, a pre-selection and pre-optimization of all available pencil beams $\boldsymbol{P}_0$ deliverable by the accelerator beam library is performed. In order to obtain $\boldsymbol{P}_1(\boldsymbol{N}_1)$, if a TPS is available, the analytical dose engine and its optimization can be used. Alternatively, to allow for a stand-alone use of the MCTP tool, independently from any external tools, a fast MC code (denominated FRED) was developed that incorporates the most important physics processes such as energy losses.

For the results presented in this work, the commercial CE-labelled TPS 'Syngo RT Planning' by Siemens AG (Version VB10A) was used for pre-optimization as employed for patient treatment at CNAO. Input to Syngo (or the fast MC) are the machine parameters, *i.e.* the accelerator beam energies and full width at half maximum (FWHM) of lateral beam profiles in air at the isocentre, the contoured phantom or patient CT images, the optimization goals and the radiobiological tables. These consist of model-generated α_{ion} and β_{ion} values as a function of energy from 0.1 MeV/u up to 1 GeV/u. The generation of cell-specific biological databases has been obtained by means of a re-implemented LEM code, as described in [10].

The FLUKA MC code has been successfully employed to support the start-up and clinical operation of ion beam therapy facilities. In particular, FLUKA has been shown to be able to accurately recalculate treatment plans with protons and carbon ions in water phantoms and patient CTs [3, 5, 12].

The newly-developed MCTP tool has been applied to perform dose computation and optimization of absorbed D_{abs} and RBE-weighted D_{RBE} dose for some test cases. In particular, we quote here the planning of two chordoma patients with two and three proton beam port respectively. A D_{RBE} of 2 Gy (RBE) for the PTV with a constant RBE of 1.1 or with a variable RBE, predicted using LEM, has been prescribed.

FLUKA simulation includes the model of the CNAO nozzle as well as the voxelized patient CT image, which is previously converted into a FLUKA-readable format. CT segmentation as proposed by [13] and extended in [5] has been followed to reduce the number of materials to be assigned to voxels.

The total number of pencil beams N_{PB} to be simulated in FLUKA was 6257 and 13920 for the two patient cases. The PTVs for the patient cases were 32.5 ml and 103.5 ml, respectively. The irradiation was performed applying the same settings as in clinical practice, *i.e.* using the same lateral profile and spacing of individual pencil beams.

The absorbed dose in a voxel j is given by

$$D_j(\boldsymbol{N}) = \sum_{i \in \mathrm{PB}} d_{i,j}\, N_i\,, \tag{1}$$

where $\boldsymbol{N} = \sum_i N_i \boldsymbol{e}_i$ is the vector of beam particle numbers for each pencil beam i with unit vector $\boldsymbol{e}_i$, and i runs over all pencil beams (PB) of the accelerator library for the chosen beam ports with $N_i > 0$, *i.e.* $i \in$ PB. To obtain a desired dose distribution in the treated volume, a suitable $\boldsymbol{N}$ has to be determined. The cost function for the optimization problem can be defined as

$$\chi^2(\boldsymbol{N}) = \sum_{j \in \mathrm{PTV}} \frac{w_j \left(\hat{D}_j - D_j\right)^2}{\hat{D}_j^2} + \sum_{j \in \mathrm{OAR}} \frac{w_j \left(\hat{D}_j - D_j\right)^2}{\hat{D}_j^2} \Theta\left(\hat{D}_j - D_j\right) , \quad (2)$$

where $\hat{D}_j$ denotes the prescribed dose in dose grid voxel j, $D_j \equiv D_j(\boldsymbol{N})$ and w_j is the weighting factor associated with the grid voxel j based on the planner's prescriptions. The first sum runs over all grid voxels inside a PTV while the second sum runs over all voxels inside an organ at risk (OAR). $\Theta(x)$ is the Heaviside function, so the terms from the second sum only contribute if the computed dose is larger than the prescribed dose. To perform single-field or simultaneous multiple-fields optimization, the inverse problem can be solved iteratively by reverting to standard algorithms. For optimization using RBE-weighted dose instead of absorbed dose, the above optimization scheme can be equally applied by replacing 'dose' by 'RBE-weighted dose', where also the gradient of weights has to be considered.

3. Results, discussion and conclusions

As an example, in Fig. 2 we show the D_{RBE} distributions for the Syngo TPS (labelled 'TPS'), MC-based recalculations (labelled 'MC REC') and MCTP optimized plans (labelled 'MC OPT') for the case with three proton beam ports. The solid lines mark the PTV while the dashed lines mark OAR.

All calculations have been performed using a constant RBE of 1.1. Recalculations of the optimized treatment plans using the same Syngo particle fluencies but RBE-weighted dose according to the LEM instead of a constant RBE result in an average RBE in the PTV of 1.13 (1.12) for the two- (three-)fields patient plan. Optimization using a constant RBE of 1.1 resulted in about 9%/4% higher total energy deposited in the patient compared to the optimization using a variable RBE according to the LEM for the two/three fields patient configuration, respectively.

The differences between TPS and MC-based recalculations can be mostly attributed to the different handling of scattering effects [12]. For the lateral dose spread, the TPS is based on a ray-tracing approach, which accounts for scattering effects by a depth-dependent double Gaussian parametrization. FLUKA instead relies on a sophisticated Multiple Coulomb Scattering

algorithm based on the Molière theory [14, 15]. Moreover, MC takes into account more realistically the material composition of the patient compared to the water-equivalent approach that is used by the TPS.

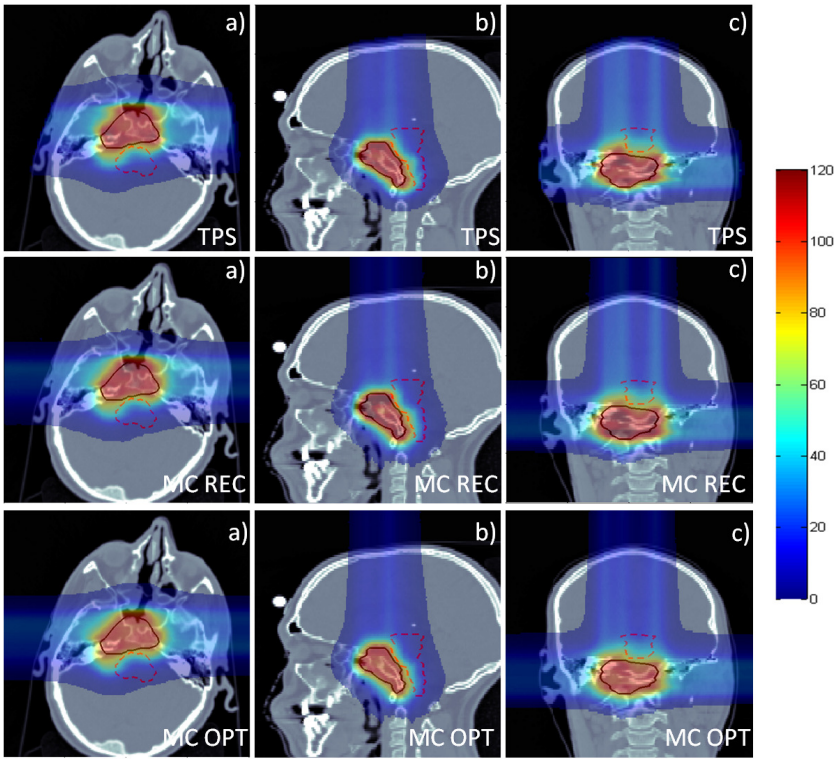

Fig. 2. D_{RBE} distributions for a patient plan calculation with three beam ports are depicted in panels (a), (b) and (c) for the axial, sagittal and coronal view, respectively. The Syngo TPS results are depicted in the first row, the MC-based recalculations are reported in the second row, while in the last row MCTP results are shown. The solid lines mark the PTV while the dashed lines mark the OAR. The colour-wash scale displays RBE-weighted dose values in percentages.

For the patient test plans, calculations using 5×10^3 primary protons per pencil beam for $2 \times 2 \times 2\,\mathrm{mm}^3$ voxels resulted in a mean statistical uncertainty in the PTV of about 1% and a maximum uncertainty below 2%. For the studied patient cases, the average computation time per primary[1] was 10 ms, resulting in an overall computation time on a cluster with 24 CPUs of about 11 (4) hours for 5×10^3 primary protons per pencil beam for the two- (three-)fields plan.

[1] Values are given for an Intel(R) Xeon(R) CPU X5650 @ 2.67GHz.

The MCTP tool is aimed to be used in the future for research and to support treatment planning at state-of-the-art ion beam therapy facilities. The extension of this tool for ions with an atomic number $Z \leq 8$ is in progress [16].

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