Physica Medica 31 (2015) 130–136

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

Scan path optimization with/without clustering for active beam delivery in charged particle therapy

Marta F. Dias [a, b, c, *, 1], Marco Riboldi [c, d], Joao Seco [e], Inês Castelhano [f, c], Andrea Pella [c], Alfredo Mirandola [g], Luís Peralta [a, b], Mario Ciocca [g], Roberto Orecchia [h, i, j], Guido Baroni [c, d]

[a] *Department of Physics, Faculty of Sciences, University of Lisbon, Lisbon 1749, Portugal*
[b] *Laboratório de Instrumentação e Física de Partículas, Lisbon 1749, Portugal*
[c] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milan 20133, Italy*
[d] *Bioengineering Unit, Centro Nazionale di Adroterapia Oncologica, Pavia 27100, Italy*
[e] *Department of Radiation Oncology, Massachusetts General Hospital – Harvard Medical School, Boston, MA 02114, USA*
[f] *Institute of Biophysics and Biomedical Engineering, Faculty of Sciences, University of Lisbon, Lisbon 1749, Portugal*
[g] *Medical Physics, Centro Nazionale di Adroterapia Oncologica, Pavia 27100, Italy*
[h] *Medical Department, Centro Nazionale di Adroterapia Oncologica, Pavia 27100, Italy*
[i] *Advanced Radiotherapy Center – Radiotherapy Division, European Institute of Oncology, Milano 20141, Italy*
[j] *Department of Science and Biomedical Technologies, Università degli Studi di Milano, Milano 20122, Italy*

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form
2 January 2015
Accepted 3 January 2015
Available online 20 January 2015

Keywords:
Scan path
Optimization algorithms
Path length
Transit particles
Wasted particles

ABSTRACT

Purpose: To compare different algorithms to optimize the scanning path in charged particle therapy with quasidiscrete scanning. We implemented a Hybrid Genetic Algorithm with Heuristics (HyGA) and combined it with clustering techniques. The performance was compared to Simulated Annealing (SA) and to commercially available treatment planning system (TPS).
Methods: Performance and clinical implications were assessed using data from 10 patients treated at CNAO (Centro Nazionale di Adroterapia Oncologica). Clinical treatments are performed relying on beam deflection, avoiding irradiation for transitions between adjacent spots larger than 2 cm. A clustering method was implemented with HyGA (HyGA_Cl), which assumes beam deflection during transition between clusters. Clinical performance was determined as the total number of particles delivered during spot transitions and the number of particles wasted due to beam deflection. Results were compared to scan paths obtained with CNAO TPS.
Results: SA and HyGA produced on average shorter paths compared to the currently available TPS. This did not result in a reduction of transit particles, due to the concomitant effect of beam deflection out of the extraction line. HyGA_Cl achieved 2% average reduction in transit particles when compared to CNAO TPS. As a drawback, wasted particles increased, due to more frequent use of beam deflection. Both the SA and HyGA algorithms reduced the number of wasted particles.
Conclusion: SA and HyGA proved to be the most cost-effective methods in reducing wasted particles, with benefits in terms of shorter scan paths. A decrease in transit particles delivered with beam deflection can be achieved using HyGA_Cl.

Introduction

In charged particle therapy there are two methods to shape the beam and tailor dose to the target volume: passive scattering and *active scanning* [1,2]. Passive scattering was the first method to be developed and is still broadly used in clinical centers worldwide. Although it has been proven to be robust, it presents disadvantages: the need for patient-specific collimators and compensators, the

---

Abbreviations: CNAO, Centro Nazionale di Adroterapia Oncologica; HyGA, Hybrid Genetic Algorithm with Heuristics; HyGA_Cl, Hybrid Genetic Algorithm with Heuristics and Clustering; SA, Simulated Annealing; TPS, Treatment plan system; TSP, Traveling salesman problem.

[*] Corresponding author. Present address: 88 Fairview Ave, Belmont, 02478 MA, USA. Tel.: +1 6172299058.

E-mail address: marta.dias@mail.polimi.it (M.F. Dias).

[1] Permanent address: Rua Joao Francisco no 2, Povoa da Galega, 2665-313 Milharado, Portugal. Tel.: +351 916000509.

http://dx.doi.org/10.1016/j.ejmp.2015.01.001

beam energy and intensity losses, beam contamination by fragments and neutrons produced in the scattering material, which leads to an unnecessary neutron dose [3]. Conversely, *active scanning* minimizes the use of patient-specific equipment for conformal charged particle delivery. In *active scanning* two dipole magnets steer the narrow pencil beams in the lateral plane, while range modulation is achieved with beam energy control. The target volume is divided into virtual slices of constant particle range (and energy), the so-called isoenergy slices. Each of these slices is further divided into single picture elements (pixels or spots), where an optimized number of particles is assigned by the treatment plan. The beam is then steered over each slice in such a way that the total number of prescribed particles is delivered to the patient [4].

Active scanning can be divided into two categories: discrete or spot scanning, where the beam is turned off between consecutive spots, and raster or *quasidiscrete scanning*, where the beam is only turned off when a slice is finished and a new energy must be set [3]. The broader interested in *quasidiscrete scanning* is mainly due to the faster repainting that it offers, important in the presence of moving targets [5–7]. Due to the fact that the irradiation beam is never turned off within a single slice, the particles delivered in between irradiation spots (transit particles) may lead to changes in the delivered dose distribution [8]. Moreover, the scan path also plays an important role in the presence of organs at risk located in vacancies within the overall spot distribution and in presence of moving targets, where fast repainting may be required to mitigate motion effects [3,5–8].

Centro Nazionale di Adroterapia Oncologica (CNAO) is the Italian national center for particle therapy treatments with either proton or carbon ion beams [9]. CNAO is a synchrotron-based facility equipped with 3 treatment rooms that started clinical activities in September 2011 with proton beams and in November 2012 with carbon ions. From the synchrotron the ions are extracted in isoenergetic spills with an approximate duration of 1 s, followed by a break of 4 s used for acceleration of new particles [9]. The scanning paths are determined by the Syngo RT Planning, version VC10 (Siemens AG Medical Systems, Erlangen, Germany) treatment planning system (TPS). At CNAO, as practical solution to keep track of the total number of particles administered to the patient, the particles delivered during spot transitions (i.e. transit particles) are assigned to the destination spot. However, by doing this, different paths may lead to different dose distributions due to different transit doses [8]. In order to overcome this issue a solution relying on magnetic beam deflection outside of the extraction line using a dedicated device (beam chopper) is applied after the scan paths have been determined. Transitions between consecutive spots, when they are larger than a given threshold (2 cm), are excluded from actual beam delivery relying on the beam chopper. However, this leads to a sub-optimal use of the equipment, resulting in (i) a waste of particles spilled at each synchrotron pulse for non optimized paths and (ii) an increase in the treatment time due to the delay caused by the beam deflection activation. These reasons and the fact that shorter paths can reduce transit particles [8] motivated the search of competitive methods for the optimization of the scan path, aiming at cost-effective treatment delivery in *quasidiscrete scanning*.

The importance of scan path optimization in *quasidiscrete scanning* was recently discussed in two different studies [3,8]. In both studies a simulated annealing (SA) algorithm was used to calculate the scanning paths. The obtained paths were compared with scan paths resulting from a zigzag algorithm, where the spots in each slice are irradiated line by line in consecutive rows. Shorter paths were obtained and consequently the treatment time was reduced. In a study by Pardo et al. the delivered dose distribution using both algorithms (SA and zigzag algorithm) was quantified: results showed that a reduction in the transit particles was achieved for the paths obtained with the SA algorithm [8]. The main goal of this work is to compare the clinical/economical implications of using different scan path optimization strategies with what is currently being used (scan paths provided by Syngo RT Planning) in real treatment plans. The effect of using practical solutions, such as beam deflection out of the extraction line, was also analyzed. The following optimization algorithms were considered: the classical Simulated Annealing (SA), as proposed in Pardo et al. and a hybrid algorithm that combines Genetic Algorithms (GA) with heuristics [10,11].

Materials and methods

Scan path optimization

A complete 3D scanning sequence is the sum of all 2D scanning maps (energy slices) over all single beams (beam angles). In this way, the 3D scan path optimization problem can be naturally subdivided in a sequence of independent 2D path optimizations. The scan path optimization can be approached as a variation of the traveling salesman problems (TSP) [3,8]. The TSP is a combinatorial optimization problem where one has to find the route that minimizes the cost of a salesman traveling through a certain number of cities.

Considering one slice with N irradiation spots, the position of each spot is given by the Cartesian coordinates (x_i, y_i), with $i = 1, 2 \ldots N$. The sequence of all spot coordinates (x_i, y_i), with $i = 1, 2 \ldots N$ defines the scan path P. The total path length (f) of scan path P can be computed as:

$$f(P) = \sum_{i=1}^{N-1} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \tag{1}$$

This equation is the objective function to be minimized: the applied optimization algorithms are explained in the following sections.

The scan path optimization was performed considering the already proposed method for treatment planning: SA [8] and a new algorithm in treatment planning called Hybrid Genetic Algorithm with Heuristics (HyGA) [11]. The name and principle of SA come from annealing in metallurgy. It is a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce defects. The implemented algorithm was the same method proposed by Pardo et al. [8]. The temperature loop was set to 1000 iterations and the equilibrium loop to 100 × N iterations or 10 × N successes. In this notation, N is the total number of irradiation spots in a slice and successes are defined as paths length that have been reduced. The path rearrangements were done considering a path segment of random size ranging from 4 to N. The SA algorithm was implemented in C++ language.

The Hybrid Genetic Algorithm with Heuristics, proposed by Sengoku and Yoshihara [11], uses a genetic algorithm and heuristics for a rapid solution of the TSP. GAs are based on the principle of "Survival of the fittest", introduced by Charles Darwin, where in nature the fittest individual to the environment has a higher probability to survive and reproduce. During the reproduction process, the offspring is generated from the crossover of two individuals, with possible mutation according to a pre-defined probability. The idea of using heuristic methods with GA is to obtain a faster convergence by introducing some knowledge about what are considered to be good solutions. The proposed crossover method, the so called Greedy Sub-tour Crossover, acquires the longest possible sequence of the parents subtours, while the 2opt method used for mutation,