Physica Medica (2011) **27**, 97—102

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ORIGINAL PAPER

# Dose calculation algorithm of fast fine-heterogeneity correction for heavy charged particle radiotherapy

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Received 28 December 2009; received in revised form 28 April 2010; accepted 6 May 2010
Available online 25 June 2010

**KEYWORDS**
Proton;
Ion beam;
Pencil beam algorithm;
Treatment planning;
Inhomogeneity correction

**Abstract** This work addresses computing techniques for dose calculations in treatment planning with proton and ion beams, based on an efficient kernel-convolution method referred to as grid-dose spreading (GDS) and accurate heterogeneity-correction method referred to as Gaussian beam splitting. The original GDS algorithm suffered from distortion of dose distribution for beams tilted with respect to the dose-grid axes. Use of intermediate grids normal to the beam field has solved the beam-tilting distortion. Interplay of arrangement between beams and grids was found as another intrinsic source of artifact. Inclusion of rectangular-kernel convolution in beam transport, to share the beam contribution among the nearest grids in a regulatory manner, has solved the interplay problem. This algorithmic framework was applied to a tilted proton pencil beam and a broad carbon-ion beam. In these cases, while the elementary pencil beams individually split into several tens, the calculation time increased only by several times with the GDS algorithm. The GDS and beam-splitting methods will complementarily enable accurate and efficient dose calculations for radiotherapy with protons and ions.


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1120-1797/$ - see front matter 
doi:10.1016/j.ejmp.2010.05.001

## Introduction

Dose distributions of radiotherapy are represented by point doses at orthogonally arranged grids. In treatment-planning practice, the grid intervals are defined from a physical, clinical, and practical points of view, often resulting in cubic dimensions of a few millimeters. Accuracy, efficiency and their balance are essential in practice, for which the pencil-beam algorithm is commonly used. That is mathematically a convolution integral of total energy released per mass (terma) with elementary beam-spread kernel, which may be computationally demanding.

The grid-dose spreading (GDS) algorithm was developed for fast dose calculation of heavy charged particle beams in patient body [1]. The GDS algorithm employs approximation to extract beam-interaction part from the integral at the expense of distortion of dose distribution for a beam tilted with respect to the grid axes, as originally recognized in Ref. [1]. The beam-tilting distortion may be generally insignificant when beam blurring is as small as the required spatial resolution, for example, for a carbon-ion beam. In fact, the GDS method was successfully incorporated into a clinical treatment-planning system for carbon-ion radiotherapy with vertical and horizontal fixed beams [2,3], for which tilting was intrinsically absent.

In that particular implementation, a simplistic post process was added to the original broad-beam algorithm so as to spread an intermediate terma distribution uniformly [1]. In general, the spreading kernel could be spatially modulated using the pencil-beam model for more accurate heterogeneity correction [4]. There are two reciprocal approaches for convolution, *i.e.* to collect doses transferred from nearby interactions to a grid or *the dose-deposition point of view* and to spread a terma from an interaction to nearby grids or *the interaction point of view*. The latter is usually more efficient than the former for three-dimensional dose calculation [5].

The pencil-beam model implicitly assumes homogeneity of the medium within the elementary beam spread. Beams that have grown excessively thick in heterogeneous transport are thus incompatible. As a general and rigorous solution, Gaussian-beam splitting was proposed, with which overgrown beams are subdivided into smaller ones at locations of large lateral heterogeneity [6]. Fig. 1 demonstrates its effectiveness for a simple density boundary, where the non-splitting beam happened to traverse an edge of a bone-equivalent material while about a half of the split beams traverse the bone-equivalent material. The splitting causes explosive beam multiplication in a shower-like process. In this particular case for example, the original beam recursively split into 28 final beams. Slowing down of dose calculation due to beam multiplication will be a problem in practice.

In Ref. [6], the beam-splitting method was stated as efficient due to certain "algorithmic techniques to be explained elsewhere", which in fact implied this work to construct a framework, where the GDS and beam-splitting methods work compatibly for accurate and efficient dose calculations. In addition, we will refine the GDS algorithm with a fix against the beam-tilting distortion and with the pencil-beam model in the interaction point of view for better heterogeneity correction.

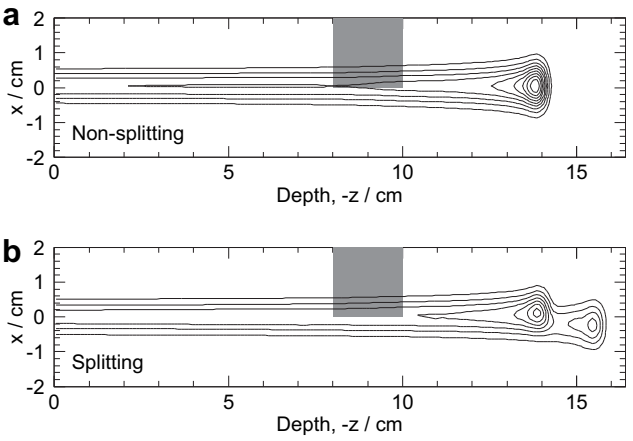


**Figure 1** (a) Non-splitting and (b) splitting dose calculations with isodose lines at every 10% levels of the maximum non-splitting dose in the $y = 0$ cross section, where a proton pencil beam with $E = 150$ MeV and $\sigma = 3$ mm is incident into water with a bone-equivalent material ($\rho = 1.8$ g/cm$^3$) inserted halfway (gray area).

Although the Gaussian-beam approximation may be reasonable for the multiple-scattering effect, two or more Gaussian components would improve the accuracy of lateral dose distribution of proton and ion pencil beams [7,8]. However, such large-sized components are intrinsically incompatible with fine heterogeneity. In addition, it is inconceivable to apply the beam-splitting method for large-sized components to secure practical efficiency.

This framework will be applicable not only to broad-beam delivery but also to pencil-beam scanning, where a physical scanned beam may have to be decomposed into virtual elementary beams to address heterogeneity [9]. As this work aims to improve computing methods, we focus on evaluation of efficiency and settlement of the intrinsic artifacts with respect to the ideal beam models that are mathematically given, without repeating experimental assessments of accuracy [6].

## Materials and methods

### Algorithmic techniques

#### Grid normalization

We will solve the beam-tilting distortion of the GDS algorithm by defining intermediate grids for dose calculation, which are arranged to be normal to the beam-field axes. As shown in Fig. 2, the original dose grids along numbered axes 1, 2, and 3 are defined with basis vectors $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ and intervals $\delta_1$, $\delta_2$, and $\delta_3$. For a given radiation field, the field coordinates $x$, $y$, and $z$ with basis vectors $\vec{e}_x$, $\vec{e}_y$, and $\vec{e}_z$ are associated, where the origin is at the isocenter and $\vec{e}_z$ is in the source direction. With lateral margins for penumbra, the normal-grid volume is defined as the supremum of normal rectangular-parallelepiped volume of $W \times L \times H$ containing the original grids in the margined field. Quadratic projection of the original-grid voxel gives the normal grid intervals $\delta_x$, $\delta_y$, and $\delta_z$ as