A track length estimator method for dose calculations in low-energy X-ray irradiations: implementation, properties and performance

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Abstract

The track length estimator (TLE) method, an "on-the-fly" fluence tally in Monte Carlo (MC) simulations, recently implemented in GATE 6.2, is known as a powerful tool to accelerate dose calculations in the domain of low-energy X-ray irradiations using the kerma approximation. Overall efficiency gains of the TLE with respect to analogous MC were reported in the literature for regions of interest in various applications (photon beam radiation therapy, X-ray imaging). The behaviour of the TLE method in terms of statistical properties, dose deposition patterns, and computational efficiency compared to analogous MC simulations was investigated. The statistical properties of the dose deposition were first assessed. Derivations of the variance reduction factor of TLE versus analogous MC were carried out, starting from the expression of the dose estimate variance in the TLE and analogous MC schemes. Two test cases were chosen to benchmark the TLE performance in comparison with analogous MC: (i) a small animal irradiation under stereotactic synchrotron radiation therapy conditions and (ii) the irradiation of a human pelvis during a cone beam computed tomography acquisition. Dose distribution patterns and efficiency gain maps were analysed. The efficiency gain exhibits strong variations within

Die Track-Length-Estimator-Methode für Dosisberechnungen bei niederenergetischen Bestrahlungen: Einrichtung, Eigenschaften und Rechenleistung

Zusammenfassung

Die Track-Length-Estimator (TLE)-Methode ist ein rechnerisch sehr effizientes Verfahren für Monte-Carlo (MC)-Simulationen, welches kürzlich in GATE 6.2 implementiert wurde. Sie wird zur Beschleunigung der Dosisberechnungen im Umfeld der niederenergetischen Röntgenstrahlung mit Hilfe der Kerma-Annährung eingesetzt. Über die Effizienzsteigerung der TLE-Mehode im Vergleich mit der analogen MC-Methode wurde in der Literatur in Bezug auf zahlreiche Anwendungen (darunter Strahlentherapie, Röntgenbildgebung) berichtet. Wir haben die TLE-Methode hinsichtlich statistischer Größen, Strahlendosisverteilungen und Recheneffizienz im Vergleich mit analogen MC-Simulationen untersucht. Zunächst wurden die statistischen Eigenschaften der abgegebenen Röntgendosis analysiert. Ausgehend vom jeweiligen Ausdruck der mit der Dosisabschätzung verbundenen Varianz bei der TLE- und der analogen MC-Methode, wurde der

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a given irradiation case, depending on the geometrical (voxel size, ballistics) and physical (material and beam properties) parameters on the voxel scale. Typical values lie between 10 and 10^3, with lower levels in dense regions (bone) outside the irradiated channels (scattered dose only), and higher levels in soft tissues directly exposed to the beams.

Keywords: Monte Carlo simulation, GATE, Track length estimator, Dose calculation, Kerma approximation, Variance reduction

Varianzreduktionsfaktor der TLE- gegenüber der analogen MC-Methode hergeleitet. Zwei Testfälle wurden zum Vergleich der Leistungsfähigkeiten der TLE- und der analogen MC-Methode untersucht: (i) die Bestrahlung eines Kleintieres bei stereotaktischer Synchrotronstrahlentherapie und (ii) die Bestrahlung eines menschlichen Beckens bei einer Cone-Beam-Computertomographie. Dosisverteilungen und Verteilungen der Effizienzsteigerungsfaktoren wurden analysiert. Letztere zeigen große Unterschiede innerhalb eines gegebenen Bestrahlungsfeldes und zwar in Abhängigkeit der geometrischen (Voxelgröße, Ballistik) und physikalischen (Material- und Strahleigenschaften) Parameter auf der Voxelskala. Typische Werte liegen zwischen 10 und 10^3, wobei niedrigere Werte in dichten Materialien (Knochen) außerhalb der bestrahlten Bereiche (nur Streudosis) und höhere Werte in weichen, direkt im Strahlenfeld liegenden Geweben festzustellen sind.

Schlüsselwörter: Monte-Carlo-Simulationen, GATE, Track-Length-Estimator, Dosisberechnung, Kerma-Annährung, Varianzreduktion

1 Introduction

The TLE method is standard of practice in low-energy photon voxel-based dose computation in the kerma approximation [1–5]. The efficiency improvement it provides with respect to analogous MC simulation is well known. However, the statistical properties of the TLE and the parameters influencing its behaviour are still insufficiently documented.

The aim of the present investigation is to bridge this gap, in particular to get an insight into the relative efficiency of the TLE method with respect to analogous MC simulation, through a theoretical derivation and detailed analysis of clinically-realistic test cases. We will focus on two application examples, namely cone beam computed tomography (CBCT) and stereotactic synchrotron radiation therapy (SSRT) [6,7].

The present layout is outlined as follows: the TLE method is briefly summarized (Sec. 2.1) and its implementation in GATE is presented (Sec. 2.2). The statistical properties of the dose deposition in both TLE and analogous MC as well as the variance reduction factor (VRF) are first investigated analytically (Sec. 2.3) and test cases are described (Sec. 2.4). The properties and performance of the TLE are studied in terms of dose distribution patterns (Sec. 3.1), computation time and related statistical uncertainties (Sec. 3.2), distributions of energy deposits (Sec. 3.3), as well as variance reduction factors and efficiency gains (Sec. 3.4).

2 Materials and Methods

2.1 The track length estimator (TLE) method

The TLE technique has long been known as an efficient tool for calculating particle fluences, kerma and absorbed dose [8,9]. It is implemented in various MC codes, such as MCNPX [1,5], and in some tools dedicated to external radiotherapy [3] and brachytherapy [2,4]. For a photon traversing a voxel of volume V, an estimate of the fluence is given by [1,9]:

$$\Phi = \frac{L}{V}, \qquad (1)$$

where L is the track length, i.e. the straight-line distance travelled in the voxel between successive collisions. Considering photons with energy E, an estimate of the absorbed dose in charged particle equilibrium is given by [8,10]:

$$D = \Phi E \frac{\mu_{en}}{\rho}, \qquad (2)$$

where Φ is the particle fluence and μ_{en}/ρ is the mass energy-absorption coefficient. With the TLE scoring method, a photon deposits energy in all voxels it encounters between successive interaction points (this energy represents the expected value of the deposits that would be observed if a large number of identical photons were transported along the same track),