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Collapsed cone dose calculations for heterogeneous tissues in brachytherapy using primary and scatter separation source data

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ABSTRACT

Background and Objective: Brachytherapy is a form of radiation therapy using sealed radiation sources inserted within or in the vicinity of the tumor of, e.g., gynecological, prostate or head- and neck cancers. Accurate dose calculation is a crucial part of the treatment planning. Several reviews have called for clinical software with model-based algorithms that better take into account the effects of patient individual distribution of tissues, source-channel and shielding attenuation than the commonly employed TG-43 formalism which simply map homogeneous water dose distributions onto the patient. In this paper we give a comprehensive and thorough derivation of such an algorithm based on collapsed cone point-kernel superposition, and describe details of its implementation into a commercial treatment planning system for clinical use.

Methods: A brachytherapy version of the collapsed-cone algorithm using analytical raytraces of the primary photon radiation followed by successive scattering dose calculation for once- and multiply scattered photons is described in detail, including derivation of the corresponding set of recursive equations for energy transport along cone axes/transport lines and the coupling to clinical source modeling. Specific implementation issues for setting up of the calculation grid, handling of intravoxel gradients and voxels partly containing non-patient applicator material are given.

Results: Sample runs for two clinical cases are shown, one being a gynecological application with a tungsten-shielded applicator and one a breast implant. These two cases demonstrate the impact of improved dose calculation versus TG-43 formalism.

Conclusions: Use of model-based dose calculation algorithms for brachytherapy taking the three-dimensional treatment geometry into account increases the dosimetric accuracy in planning and follow up of treatments. The comprehensive description and derivations provided gives a rigid background for further clinical, educational and research applications.

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1. Introduction

Brachytherapy uses sealed radioactive photon-emitting sources inserted into or close to a tumor to control its growth and ultimately eradicate it. Source locations and times determine the administered dose distribution necessitating careful and accurate dose calculations prior to the treatment. However, in clinical practice this is commonly done in a simplistic manner as if the sources were placed in water thus neglecting patient specific radiation absorption patterns. Determination of the dose in water is based on a protocol set forth by the American Association of Physicists in Medicine Task Group No. 43 (AAPM TG-43) [1,2]. The AAPM TG-43 approach is accurate in describing influence of source geometry but disregards patient specific tissue distributions, source guiding applicators and metal shields. To improve dose calculation accuracy model-based dose calculation algorithms (MBDCA) can be used, and the AAPM Task Group 186 (TG-186) has issued guidance for use of these algorithms [3].

While each patient is unique, there is only a restricted number of source types available. Adoption of the TG-43 formalism has made available source data in parameterized condensed form that links to measureable quantities for which metrological traceability is established [4] which ensures site independent consistency. The primary and scatter separation (PSS) method [5] extends the TG-43 formalism so that data can be used as input to MBDCA. The PSS approach is not energy specific and extended data sets are accessible through the web[1] for several sources of the common isotopes employed in brachytherapy. See also the supplementary material for further information.

The main proposals for MBDCA, besides Monte Carlo simulations, are grid based Boltzmann equation solvers and point kernel superposition methods, where the latter offer higher calculation efficiency (see, e.g. [3,6,7]). Full radiation transport calculations using Monte Carlo methods is computation-time demanding, but are often used for verification of other methods. A variant of point kernel superposition is the so called collapsed cone (CC) approach [8] originally developed for external photon beam radiotherapy (EBRT) for which it has been extensively tested versus full Monte Carlo simulations [9–11] and used in major commercial treatment planning systems (e.g. Oncentra, Raystation, Monaco). Adaptation of the CC algorithm to BT has been described in a series of papers [12–14] and can use source data based on the PSS formalism [5,15].

This paper provides a comprehensive derivation and description of an implementation of the CC algorithm intended for clinical use, including extensions to handle elongated sources, applicators and shields, and heterogeneous patient geometries based on tomographic images. Transport of primary and first scatter photons is considered explicitly, while higher orders are collectively treated as a multiple-scatter class. Explicit transport of electrons is disregarded and the dose reported by the described algorithm is the collision kerma to the local medium. The algorithm has recently been implemented into Oncentra® Brachy, the Elekta Brachytherapy system for BT treatment planning for ^{192}Ir and ^{60}Co sources and is described in a "white paper" [16]. Verification versus full Monte Carlo simulations has been reported elsewhere [17–20] .

[1] http://www.physics.carleton.ca/clrp/seed_database; Web links accessed July 18, 2016.

2. Computational methods and theory

2.1. Overview

The basic quantity calculated by the algorithm is dose per primary radiant energy R_{prim} emitted by the source. For clinical use this is renormalized to dose rate per source by means of the air-kerma strength and dose rate constant from the AAPM TG-43 formalism [1,2]. Dose, D, is calculated separately for several scatter generations such that:

$$\frac{D}{R_{prim}} = \frac{D_{prim} + D_{1sc} + D_{msc}}{R_{prim}} \quad (1)$$

where D_{prim} is primary dose, D_{1sc} is dose from once scattered photons, and D_{msc} is the multiple-scatter dose from all higher order of scattering events (i.e. more than once). The basic data for source characterization is based on the PSS concept [5], in which R_{prim} is defined as the amount of photon radiant energy leaving the source, and treated as primary until the photon's first interaction *outside* of the source and its encapsulation. The source specific data needed is the primary dose distribution derived in homogeneous water phantoms together with the spectrum of primary photons exiting the source encapsulation. Supplemented by isotope specific (rather than source specific) spectra for once and multiply scattered photons, energy deposition kernels for water, and media composition data, the algorithm uses a successive scattering approach [12,21] to calculate the different scatter order doses, in which a lower scatter order dose is used as precursor to a higher order. The algorithm itself is agnostic in regards to the energy of the source for which dose calculations are taking place. All energy dependencies are taken care of through the set of input parameters that the algorithm requires (see Supplementary material). Energy or source specific changes to the implementation and/or configuration of the algorithm can be beneficial [14] but are not implemented currently. Based on prescriptions, the final dose can be renormalized to enable determination of source specific dwell times as outlined in Ref. [22] and explicitly described in Section 7. In the sections to follow, details of the algorithm are given starting with the primary dose calculation followed by the first- and multiple-scatter dose components.

2.2. Primary dose calculation

The primary dose is calculated as an anisotropic point source primary collision-kerma model complemented by a correction in the near zone close to the source. In this region significant deviations from the dominating $1/r^2$-effect may exist due to influences from a finite extension of the source, dose gradient averaging over finite voxels, and to some extent electron transport for sources of higher energy. The source specific spectrum