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Determination and verification of a 2D pencil-beam kernel for a radiosurgery system with cones

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ABSTRACT

The quality and correctness of dosimetric data of small fields in stereotactic radiosurgery (SRS) depends significantly on the election of the detector employed in the measurements. This work provides an independent method of verification of these data through the determination of a polyenergetic 2-dimensional pencil-beam kernel for a BrainLAB SRS system with cones, employing the deconvolution/convolution of a reference experimental off-axis ratio (OAR) profile (cone diameter $c_0 = 35$ mm). The kernel in real space $k_{c_0}(r,z_0)$ is convolved with the ideal fluence Φ for the cones 7.5 to 35 mm in diameter to obtain the OAR profiles, and the total scatter factors, S_t, which are compared with experimental values of the same quantities. The experimental OARs and S_t factors are measured in water with a PTW 60003 diamond detector. Additionally, the reference OAR is corrected for beam divergence and spectral fluence fluctuations defining a function of boundary correction factors (BF). The BF and Φ functions are transformed to the conjugate space with the zeroth-order Hankel transform, appropriated to the radial symmetry of the cones. Therefore, the kernel in real space $k_{c_0}(r,z_0)$ is the inverse Hankel transform of the ratio of the Hankel transforms of BF and Φ. Finally, an uncertainty analysis according to the Guide to the Expression of Uncertainty in Measurement is carried out for 3 different values of $k_{c_0}(r,z_0)$. Calculated and measured OARs agree within the dose/distance-to-agreement criteria of 2%/0.12 mm; while, S_t factors agree within 2%. This procedure supplies an independent method to validate the dosimetric data necessary to feed treatment planning systems for SRS with cones.

Introduction

In typical conical fields of stereotactic radiosurgery (SRS), the correctness of dosimetric data introduced to the treatment planning system depends significantly on the election of the detector employed in the measurements, to minimize the perturbations introduced by[1,2] (1) the averaging effect in the measurements caused by the lack of spatial resolution of the detector, (2) the water nonequivalence of the detector material, (3) the lack of lateral electronic equilibrium in the beam axis (for fields with radius ≤ the range of the electrons generated in the medium), and (4) the partial blocking of the beam source, that causes the reduction in the photon beam intensity.[3]

Therefore, an objective of this work is to develop a verification/validation method for the experimental off-axis ratios (OARs) and S_t factors for the conical fields of a SRS system with cones. The method starts with the determination of an absorbed dose 2-dimensional (2D) pencil-beam kernel employing the deconvolution/convolution of an experimental reference OAR (cone diameter $c_0 = 35$ mm) measured with a diamond detector, where this detector minimizes the perturbations mentioned before. The procedure of deconvolution/convolution is performed using zeroth-order Hankel transforms, appropriated for the radial symmetry of the circular fields generated by the cones.[4] From this kernel, the OARs and S_t factors for all employed cones are calculated using the convolution method and then are compared with the OARs and S_t factors measured with the diamond detector. Finally, an uncertainty analysis for the obtained kernel is carried out according to the Guide to the Expression of Uncertainty in Measurement (GUM guide).[5]

Methods and Materials

SRS system with cones

A 6 MV ($TPR_{20/10} = 0.669$) photon beam from a Varian 2100 C/D linear accelerator (LINAC) (Varian Medical Systems, Palo Alto, CA) is used along with a Circular Arc SRS system with cones (BrainLAB, Germany) mounted to the secondary collimators of the LINAC head.

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The BrainLAB cones produce circular fields of: 7.5, 12.5, 15, 17.5, 20, 22.5, 25, 30, and 35 mm in diameter, at the isocenter, source to axis distance = 100 cm. The LINAC jaws are fixed to the opening of 4 cm × 4 cm.

Measurement equipment for OARs and S_t factors

To set the detector, a water phantom MP3-S with a positioning system Trufix (PTW-Freiburg, Germany) is employed. This guarantees a positioning accuracy of the detector within ± 1 mm[6]; the control software is Mephysto version 7.3.

In particular, a diamond detector fulfills the requirements of water equivalence and spatial resolution[1,2,7]; therefore, the cylindrical diamond detector PTW 60003 (PTW-Freiburg, Germany) with a circular area of 5.8 mm^2 and thickness of 0.26 mm is chosen for the measurements.[8] The detector is polarized to a bias voltage of +100 V; and also, to stabilize its response, it is preirradiated with 15 Gy.[9]

To correct for beam divergence and fluctuations of the spectral fluence, the OAR of a 40 cm × 40 cm open field is measured with a PTW 31002 ionization chamber (PTW-Freiburg, Germany), which has an active volume of 0.125 cm^3 and a diameter of 0.55 cm.

Measurement of OARs and S_t factors

The diamond detector is positioned with its main axis perpendicular to the beam axis to measure OARs; whereas, it is set up with its main axis parallel to the beam axis to measure S_t factors. These set ups guarantee a maximum resolution of 0.26 mm in the directions of measurement.[1,2]

To align the detector with respect to the beam radiation axis, 2 scans are carried out: one in the crossplane axis and another in the inplane axis, with a collimator of 7.5 mm diameter, at a depth of 7.5 cm. Then, the radial distance is obtained at 50% of absorbed dose, and the detector positioning deviations are corrected according to this distance. Additionally, to decrease the output beam fluctuations, all measurements are done with an integration time of 1 second, with a detector speed of 5 mm/s.

The OAR profiles are measured in the crossplane axis with a constant step of 0.5 mm up to the radial distance of 20, 25, 25, 30, 30, 40, 40, 40, and 50 mm for cones of 7.5, 12.5, 15, 17.5, 20, 22.5, 25, 30, and 35 mm in diameter, respectively. Full profiles are measured for each cone and then the half profiles are averaged.

However, with regard to the diamond detector response, many authors have reported a nonlinear response with the dose rate, according to the following equation[10,11]:

$$i \propto \dot{D}^{\Delta} \tag{1}$$

where i is the current measured by the diamond detector, $\dot{D}$ is the dose rate at the point of measurement, and the dimensionless parameter Δ is specific for each individual detector.

For our diamond detector $\Delta = 0.989 \pm 0.006$, is experimentally determined by a regression analysis from the experimental data corresponding to the measurements of current i with the diamond detector at 7 different depths for a field size of 10 cm × 10 cm, SSD = 100 cm; the dose rate $\dot{D}$ at the same positions and under the same geometrical conditions is determined with a calibrated pinpoint PTW 31014 ionization chamber.

Once Δ is obtained, the OARs for each cone of size c are calculated in the following way:

$$OAR(c,r) = \left[\frac{i(r)}{i(0)}\right]^{1/\Delta} = [y(r)]^{1/\Delta} \tag{2}$$

where $y(r) = i(r)/i(0)$ is the current profile normalized to the value at the central axis.

The power $1/\Delta$ in Eq. (2) means that the relationship between the dosimetric function OAR and the current profile measured by a diamond detector is nonlinear, due to the nonlinear dependence of the response of the diamond detector with the dose rate given by Eq. (1).

Establishment of the reference OAR

The biggest cone of our SRS system, which is 35 mm in diameter, is elected to obtain the 2D pencil-beam kernel representative of the entire system at the depth of $z_0 = 7.5$ cm. We call "reference OAR" to the profile of this cone.

The reasons to use this OAR instead of the OAR of a smaller cone are as follows:

(1) In smaller field sizes, the regions of lateral electronic disequilibrium are bigger.
(2) In smaller field sizes, the level of partial blocking of the beam source is bigger.
(3) The measurements in smaller field sizes have higher uncertainty.

The depth $z_0 = 7.5$ cm in water is of interest because it is the single depth recommended by the manufacturer for the commissioning of the Brainscan version 3.53 treatment planning system (BrainLAB AG, Germany) associated to the BrainLAB SRS system.

Correction of the reference OAR—35 mm diameter cone—for beam divergence and spectral fluence variations

To correct the experimental reference OAR for beam divergence and spectral fluence variations—before the OAR deconvolution—the Chui and Mohan method is applied.[12] This procedure consists of calculating the ratio of the reference OAR to the 40 cm × 40 cm open field OAR, both measured at the same source to axis distance of 100 cm and depth z_0 of 7.5 cm; this ratio is called function of boundary correction factors (BF).[12]

$$BF(c_0,r) = \frac{OAR(c_0,r)}{OAR(40 \times 40\ \mathrm{cm}^2, r)} - Bkg \tag{3}$$

where $c_0 = 35$ mm is the diameter of the reference cone, r is the radial distance measured from the radiation beam central axis, and Bkg is the background considered as 1.5% of the signal value, where this background signal occurs at $r = 35$ mm.

The rationale of this method is that for such a large field any beam modifier that causes spectral fluence variations, for example the field-flattening filter, is completely expressed in the OAR profile, and also the intrinsic beam divergence; then dividing the finite size beam OARs to this largest beam OAR, these effects are removed from the finite size beam OARs.

However, this correction is negligible in SRS with cones of diameters ≤ 35 mm because the divergence of the beam is minimal, and the photon beam is flat in this region. Therefore, the values of BF are nearly identical to the normalized OARs.

Fitting of BF to an analytic function

The resulting vector BF (Eq. (3)) is fitted to an analytic function BFF with the purpose of getting continuous values of BF at arbitrary radial distances. The fitting function BFF given by the following equation results from the convolution of a triple gaussian function (kernel) with a fluence rectangular function.[13]

$$BFF(c_0,r,z_0) = \sum_{i=1}^{3} \frac{c_i(z_0)}{2}\left[erf\left(\frac{r+c_0/2}{\sigma_i(z_0)}\right) - erf\left(\frac{r-c_0/2}{\sigma_i(z_0)}\right)\right] \tag{4}$$

where $c_i(z_0)$ and $\sigma_i(z_0)$ are the fitted parameters, and $erf(z)$ is the error function[14]:

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}\,dt \tag{5}$$

To perform this fitting, we use the optimized Levenberg-Marquardt algorithm[15]; the parameters of the fitting are shown in Table 1.

Pencil-beam kernel

An absorbed dose pencil-beam kernel is defined as the distribution of imparted energy by secondary particles generated in a semi-infinite medium—usually water—due to a point monodirectional photon beam incident at the origin of coordinates of the kernel.[16]

In the literature, to the best knowledge of the authors, there are at least 4 different methods to calculate a pencil-beam kernel.

(1) The Monte Carlo method, is the most direct calculation, but requires knowledge of the spectral fluence of the particular radiation from which the kernel is calculated.[16]
(2) The fitting to an analytic model using experimental measurements. It entails the formulation of an analytic kernel and the experimental determination of the involved variables.[17]
(3) The estimation of the kernel from numeric differentiation of S_t.[18,19]
(4) The deconvolution of experimental OARs. Chui and Mohan employed Fourier transforms to deconvolve the absorbed dose kernel at a particular depth, for a 20 cm × 20 cm field.[12] Azcona and Burguete, considering the radial symmetry of the pencil-beam kernel, used Hankel transforms to calculate this kernel at a particular depth, for a circular field of 50 mm in diameter.[20,21]

This last method is particularly novel and ideal when it is applied to the case of SRS with cones, because of the radial symmetry of the fields. Hence, this method has been used in this work, where the convolution/deconvolution of Hankel transforms is implemented in Mathcad version 14.0.0.163.

Table 1
Fitting parameters of $BFF(c_0,r,z_0)$ function Eq. (4)

Parameter	Value	95% Confidence interval
σ_1	0.539	0.038
σ_2	2.735	0.295
σ_3	8.479	0.701
C_1	0.472	0.025
C_2	0.324	0.027
C_3	0.188	0.028