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A multi-plane source model for out-of-field head scatter dose calculations in external beam photon therapy

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Abstract
Our purpose was to assess the out-of-field dose component related to head scatter radiation in high-energy photon therapy beams and then derive a multisource model for this dose component. For scattered photons, several planar sources have been defined, with number, location and tilt depending on the complexity of the field shape. In the absence of precise knowledge of out-of-field scattering characteristics, several assumptions are made to derive emission spectra and radiation intensity from measurements. Among these, the Compton formula is used to evaluate scattered photon energy and the Henyey–Greenstein phase function is used to evaluate the scattered photon angular distribution. For measured doses under out-of-field conditions, the average local difference between the calculated and measured photon dose is 10%, including doses as low as 0.01% of the maximum dose on the beam axis. This study demonstrates that the multi-plane source approach is suitable for accurate analytical modeling of the out-of-field dose component related to head scatter radiation. These results should be taken into account when evaluating doses to the remaining volume at risk in external beam radiotherapy planning.

(Some figures may appear in colour only in the online journal)

1. Introduction

The basic purpose of high energy external beam photon therapy (EBPT) is to deliver the prescribed dose to the planned target volume (PTV) while sparing healthy tissues (ICRU 2010). Compared to conventional techniques, it is currently possible, using modern techniques, to reduce the normal tissue dose without affecting the tumor dose. This results in improved...
tumor control and fewer complications in normal tissue. Nevertheless, EBPT is unavoidably associated with irradiation, at lower doses, of large volumes of normal tissue away from the beam path.

According to the latest recommendations of the International Commission on Radiation Units and Measurements (ICRU) concerning the remaining volume at risk (RVR), the search for means of more accurately determining such doses is of renewed clinical interest. Indeed, according to ICRU Report 83 (ICRU 2010), all normal tissues that could potentially be irradiated should be included in the RVR, and the absorbed dose in the RVR might be useful for estimating risk of later effects such as carcinogenesis.


In essence, the out-of-field dose arises from three main sources: (1) leakage from the treatment unit; (2) scatter from the treatment unit head and from beam modifiers such as wedges and blocks; and (3) internal scatter originating in the patient. Only the first two sources depend on machine design and/or additional beam modifiers placed in the path of the beam; they must be measured for each individual treatment machine, while radiation scattered inside the patient depends only on energy and can be used irrespective of the machine under consideration. It also appears that only at a short distance does the patient scatter show a substantial contribution; at a longer distance, leakage and head scatter are the major contributors. At 6 and 15 MV for example, it has recently been established that, starting from 20–25 cm off axis at 10 cm depth, the contribution of leakage and head scatter is greater than 50% of the total out-of-field dose for field sizes up to to 20 × 20 cm² open fields and prevails in the far periphery (Joosten et al 2011, Chofof et al 2012).

The aim of this work was to experimentally assess, for several therapy machines, out-of-field absorbed dose components due to external scattering radiation in EBPT and then derive a multisource model suitable for computation of related absorbed dose distributions away from the beam path.

2. Materials and methods

2.1. Experimental data acquisition

Dose measurements for the present study were performed on three treatment machines: one cobalt unit, Alcyon II, and two linear accelerators, Clinac 2300 C/D operated at 6 and 20 MV and Novalis Tx operated at 6 MV (Varian Medical Systems, Palo Alto, CA, USA). Photon doses were measured with powder-type TLD-700 thermoluminescent dosimeters (Harshaw Chemical Company, Solon, OH). Dosimeters were read out in a PCL-3 (Fimel, Velizy, France) automated TLD reader.

A 100 × 50 × 30 (cm³) water tank was used for absorbed dose-to-water measurements. The water tank was filled to a depth of 20 cm. A special TLD holder was designed in which capsules could be inserted at various depths and distances outside the beam path, enabling reproducible positioning of the capsules. The source-to-surface distance (SSD) was set at 80 and 100 cm for the cobalt unit and linear accelerators, respectively.
Five different field size settings were tested for the cobalt unit: \(5 \times 5, 10 \times 10, 15 \times 15, 20 \times 20\) and \(30 \times 30\) cm\(^2\); points of measurement for the absorbed dose were set, respectively, in the range of 15 to 70 cm, 15 to 70 cm, 15 to 70 cm and 25 to 70 cm distance from the beam axis at 10 cm depth in the water tank.

Four different field size settings were tested for the linear accelerators: \(5 \times 5, 10 \times 10, 15 \times 15\) and \(30 \times 30\) cm\(^2\). Points of measurement for the absorbed dose were set in the range of a 15 to 70 cm, 15 to 70 cm, 15 to 70 cm, 20 to 70 cm and 25 to 70 cm distance from the beam axis at 10 cm depth in the water tank.

All TLDs were prepared and read by Equal-Estro Laboratory (Equal-Estro, Villejuif, France), which has longstanding experience in TLD use and analysis (Derreumaux \textit{et al} 1995, Marre \textit{et al} 2000, Ferreira \textit{et al} 2000). Calibration for dose dependence was performed using a \(^{60}\)Co gamma beam. Linearity correction was determined using interpolation of multiple known exposures over the range of doses received by experimental TLDs. Correction for energy dependence was determined by comparing the signal of known exposure with each treatment energy to known exposure with \(^{60}\)Co. No fading correction was necessary, as reference TLDs were irradiated and read at the same time as test TLDs.

### 2.2. Semi-empirical method for evaluation of external scattering dose

The total absorbed dose \(D(f, r, z, \psi)\) to a site of interest located outside the beam path is generally described as the following sum of three main separate constituent components equation (1):

\[
D(f, r, z, \psi) = D_{\text{IS}}(f, r, z, \psi) + D_{\text{EL}}(f, r, z, \psi) + D_{\text{DM}}(f, r, z, \psi),
\]

where \(f, r, z\) and \(\psi\) are the field size, distance from the beam central axis, depth and angular orientation, respectively. \(D_{\text{IS}}(f, r, z, \psi)\) is the absorbed dose due to internal scattering in the patient, \(D_{\text{EL}}(f, r, z, \psi)\) is the absorbed dose due to external scattering in the treatment machine’s head and \(D_{\text{DM}}(f, r, z, \psi)\) is the absorbed dose due to leakage also due to the treatment machine’s head.

Since our objective was to develop a semi-empirical model, analysis of \(D_{\text{IS}}(f, r, z, \psi)\) alone was initially required in order to experimentally select this component. The experimental set-up has been reported (Kase \textit{et al} 1983, Ruben \textit{et al} 2011) and enables \(D_{\text{IS}}(f, r, z, \psi)\) to be separated via direct measurements. The experimental setup (figure 1), designed to avoid any contribution from the patient, \(D_{\text{IS}}(f, r, z, \psi)\) consists of positioning the water tank relative to the beam edge so that the primary beam does not pass through or interact with water in the tank. The resulting measured dose \(D_{\text{M}}(f, r, z, \psi)\) thus reflects the sum of \(D_{\text{IS}}(f, r, z, \psi)\) and \(D_{\text{EL}}(f, r, z, \psi)\) only:

\[
D_{\text{M}}(f, r, z, \psi) = D_{\text{EL}}(f, r, z, \psi) + D_{\text{IS}}(f, r, z, \psi).
\]

On each off axis position \((r, z, \psi)\), the measurement data for field size settings of \(5 \times 5, 10 \times 10\) and \(15 \times 15\) cm\(^2\) were used to fit the following function:

\[
D_{\text{M}}^{\text{Norm}}(f, r, z, \psi) = \lambda(r, z, \psi) + \kappa(r, z, \psi) \times \left\{\frac{1}{\lambda(r, z, \psi)} - 1\right\},
\]

where \(D_{\text{M}}^{\text{Norm}}(f, r, z, \psi)\) denotes the doses measured using the experimental setup in figure 1 normalized with respect to the central maximum dose, at distance \(r\), depth \(z\), in direction \(\psi\), for field size \(f\), \(\lambda(r, z, \psi)\), \(\kappa(r, z, \psi)\) and \(\nu(r, z, \psi)\) are theoretically-driven parameters.

We note that equation (3) is formed by the sum of two terms, the first is an independent field size term while the second varies according to the field size. Furthermore, previously published data (Kase \textit{et al} 1983) revealed that, in general, the external leakage dose was virtually independent of field size, whereas the external scattering dose strongly depended
Figure 1. Experimental setup used to measure the dose reflecting the sum of the components related to external scattering and external leakage radiation, respectively.

on field size. It was therefore assumed, in this study, that the field size independent term \( \lambda(\mathbf{r}, \mathbf{z}, \varphi) \) and varying term \( \kappa(\mathbf{r}, \mathbf{z}, \varphi) \times \left\{ \text{e}^{[\mathbf{r}(\mathbf{r}, \mathbf{z}, \varphi) \times \mathbf{f}]} - 1 \right\} \) reflect at the fixed location \((\mathbf{r}, \mathbf{z}, \varphi)\) respectively, the external leakage dose and the external scattering dose both normalized to the central axis dose maximum.

2.3. Multisource modeling

2.3.1. General concept. To describe \( D_{\text{ES}}(f, \mathbf{r}, \mathbf{z}, \varphi) \), we chose multisource modeling introduced by Dunscombe and Nieminen (1992) and successfully used by several authors to study the field size dependence of relative output from linear accelerators (Dunscombe and Nieminen 1992, Yu and Sloboda 1995, Jian et al 2001, Yang et al 2002). Basically, in these models, a distributed source representing photons was scattered in the linear accelerator head. To model scattering on the beam central axis, it was generally assumed by previous authors that the dependence of photon fluence emanating from the distributed source on radial distance was Gaussian (Dunscombe and Nieminen 1992) or a combination of Gaussians (Yang et al 2002) or of different picked distributions (Yu and Sloboda 1995, Jian et al 2001). As depicted in figure 2, the model developed in the present study focused on scattering and leakage outside the beam path. It included a set of planar sources \((S)\) to represent photons reaching the measurement point after being scattered.

2.3.2. Scattering source. The scattering source \( S \) is not a physical source, but rather a virtual source modeled to include all scatter photons constituting the out-of-field scattering diffusion. For this, it is necessary to introduce, for \( S \), geometric and emission characteristics different from those previously reported. Hence, in the absence of precise knowledge about out-of-field scattering, several assumptions are made.
Figure 2. Basic principle of the multi-plane source model. (a) A schematic representation of the surface source $S$ and of the linear accelerator head shielding and secondary collimator lower jaws is depicted and (b) indicates the geometric terms used in the final model formulation equation (7).

$S$ is assumed to consist of a set of planar elementary sources emerging at the linear accelerator target and lining the inner surfaces of secondary collimator jaws and/or MLC elements and/or blocks, as appropriate, down to the bottom of the flattening filter (figure 2). Thus, number, location and tilt of surface element constituents of $S$ depend on field shape.
Defined in this manner, this assembly of virtual sources is capable of modeling any complex field shape.

Furthermore, it is assumed that only the photons emanating from the region of \( S \) visible from the measurement point \( P(r, z, \varphi) \), and denoted below as the aperture, contribute to \( D_E(f, r, z, \varphi) \). On the other hand, we consider that a scattered photon from an invisible region of \( S \) contributes to the off-axis dose as external leakage radiation taken into account by the term \( D_{EL} \) of the equation (2).

To facilitate computation of energy fluence distribution of photons emanating from \( S \), the aperture is divided into pixels, each measuring 5 mm \( \times \) 5 mm. Software based on the z-buffer algorithm (Catmull 1984) is developed and used to identify pixels belonging to the aperture.

**Source intensity distribution.** The major portion of the in-field scatter radiation is generated by forward scattering in the flattening filter, whose scope is limited by the primary collimator (Ahnesjo 1994, Chaney et al 1994, Deng et al 2000). Therefore, we assume in this work that the planar sources of \( S \) are powered by the scattering photons originated from the bottom of the flattening filter.

Partly motivated by previous modeling works (Ahnesjo 1994, Yu and Sloboda 1995), the source intensity at the \( i \)th pixel is expressed analytically as a quasi triangular distribution:

\[
\Omega_{ES}(r_i, \sigma_i) = \begin{cases} 
(1 - \tau \times \sigma_i) \times \left( \frac{DSA}{r_i} \right)^{\alpha} & r_i \leq r_0 \\
1 - \tau \times \sigma_i & r_i > r_0 
\end{cases}
\]

where \( \sigma_i \) is the angle between the axis from the target to pixel \( i \) and the central axis, \( r_i \) is the distance between the target and pixel \( i \) and DSA is the distance source–axis assumed to be equal to 100 cm (80 cm for the cobalt unit), \( \tau \), \( r_0 \) and \( \alpha \) are constants.

**Energy distribution.** The standard Compton expression (Compton 1923) is used to evaluate scattered photon energy:

\[
E_{\theta i} = \frac{E_0}{1 + \frac{m_e c E_0}{m_e c E_0} \times (1 - \cos(\theta_i))}
\]

where \( E_{\theta i} \) is the energy of the scattered photon through angle \( \theta_i \); \( E_0 \) is a theoretically driven fit parameter reflecting the average energy of the incident photons; \( m_e \) is the mass of an electron at rest; and \( c \) is the speed of light.

**Angular distribution.** With high energy photon beams in high atomic number media (flattening filter, collimator, beam attenuators, etc), the generation of scattered photons is due to single or multiple Compton scattering as well as bremsstrahlung and annihilation radiation attributable to the secondary electrons and positrons of the photon beam.

Therefore, the Compton interaction must be corrected as proposed by authors such as Ahnesjo (1995).

We propose the use of the Henyey–Greenstein phase function which offers the advantage of a free parameter \( g \) which takes into account these complex phenomena after adjustment on experimental measurement data.

The Henyey–Greenstein phase function (Henyey and Greenstein 1941) is given by

\[
p_{HG}(\theta) = \frac{1}{4\pi} \times \frac{(1 - g^2)}{(1 + g^2 - 2 \times g \times \cos(\theta))^2}
\]
where $\theta \in [0, \pi]$ (rad) is the angle existing between the direction of the photon before a scattering event and the direction after the scattering event. The parameter $g$ is the Henyey–Greenstein asymmetry factor.

The scattering probability into the solid angle defined by an infinitesimal cone around the direction $\theta$ (see figure 2(b)) is actually given by (Binzoni et al. 2006):

$$
P_g^\theta = 2\pi \times p_{HG}(\theta) \times \sin(\theta) = \frac{1}{2} \times \frac{(1 - g^2) \times \sin(\theta)}{(1 + g^2 - 2 \times g \times \cos(\theta))^2}. \tag{6}$$

2.3.3 Multi plane source model. At point $P(r, z, \phi)$ in the water tank, the external scattering dose normalized with respect to the maximum dose on the beam axis for field size $f$ $D_{ES}^{Norm}(f, r, z, \phi)$ related to photons emanating from the pixels of source $S$ is expressed as:

$$
D_{ES}^{Norm}(f, r, z, \phi) = \omega \times \sum_{i=1}^{n(f, r, z, \phi)} \Omega_{ES}(r_i, \sigma_i) \times \frac{P_g^{\theta_i} \times E_{\theta_i} \times \exp(-\mu_{w,\theta_i} \times l_i)}{R_i^2} \tag{7}
$$

where $\Omega_{ES}(r_i, \sigma_i)$ is the source intensity at the pixel $i$, $\theta_i$ the angle between the axis from the target to pixel $i$ and the axis from that pixel to the measurement point, $P_g^{\theta_i}$ is the probability of scattering through $\theta_i$; $E_{\theta_i}$ is the scattered photon energy; $\mu_{w,\theta_i}$ is the linear attenuation coefficient in water for $E_{\theta_i}$; $l_i$ is the distance traveled in water by the photons emanating from pixel $i$ of source $S$; $R_i$ is the distance from that pixel to the measurement point; and $\omega$ is a theoretically driven fit parameter reflecting proportionality between estimated energy fluence and external scattering dose fraction of the central maximum dose. Summation is achieved over $n(f, r, z, \phi)$ pixels corresponding to the region of $S$ visible from the measurement point $P(r, z, \phi)$ (see figure 2(b)).

Little information is needed on the unit treatment head (and can be obtained from the manufacturer’s documentation) in order to fix the scattering source size and location: the distance between the target-bottom of the flattening filter, the target-jaws and/or target-multileaf collimator and leaf thickness.

Normally, the model parameters $E_0, g, \tau, r_0, \alpha$ and $\omega$ depend on the field size since it interpolates doses normalized with respect to the maximum dose. However, we chose to fit the normalized doses all together to propose a model offering a compromise between all field sizes while also being compatible with the experimental results.

A least-square technique was then employed to determine values of $E_0, g, \tau, r_0, \alpha$ and $\omega$ yielding the best fit to separate experimental data points available for $^{60}$Co gamma rays, the two 6 MV RX beams and the 20 MV RX beams.

3. Results

Figure 3 shows estimations of the leakage component obtained when fitting our experimental data with equation (3). Depending on the distance from the beam axis, estimates of the leakage dose ranged from 0.013% to 0.055%, from 0.005% to 0.13% and from 0.01% to 0.18% of the maximum dose on the central axis, for the $^{60}$Co, 6 and 20 MV beams, respectively. The mean standard error of the estimates is evaluated at 15% (min = 2%, max = 43%) for all beam energies used.

Table 1 summarizes parameters yielding the best fit to the measurement in multisource modeling. Figure 4 compares normalized dose profiles generated when using parameters from table 1 in the multisource model to measured profiles under a variety of conditions. The percent median difference in normalized local dose between measurements and calculations is 9%,
Figure 3. Estimates of leakage dose components (parameter \( \lambda(r, z, \varphi) \), equation (3)) for the Varian linear accelerator Clinac 2300 C/D operated at 6 and 20 MV RX, respectively. The doses are given as percentages of the dose at the depth of the maximum dose on the beam axis.

Table 1. Values of energy factor \( E_0 \), the Henyey–Greenstein asymmetry factor \( g \), the normalized dose–energy fluence proportionality coefficient \( \omega \) and the source intensity constants \( \kappa, r_0 \) and \( \alpha \) yielding the best fit of equation (7) to the separate experimental data points available in this study, for Alcyon II’s \(^{60}\)Co gamma beam, Varian Clinac 2300 C/D’s 6 and 20 MV RX beams and Varian Novalis Tx’s 6 MV RX beam.

<table>
<thead>
<tr>
<th></th>
<th>( E_0 ) (MeV)</th>
<th>( g )</th>
<th>( \omega ) (cm(^2) MeV(^{-1}))</th>
<th>( \tau ) (rad(^{-1}))</th>
<th>( \alpha )</th>
<th>( r_0 ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcyon II</td>
<td>1</td>
<td>0.537</td>
<td>0.139</td>
<td>0(^a)</td>
<td>1.7</td>
<td>15</td>
</tr>
<tr>
<td>6 MV Novalis Tx</td>
<td>2</td>
<td>0.223</td>
<td>0.314</td>
<td>3.5</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>6 MV Clinac 2300 C/D</td>
<td>2</td>
<td>0.418</td>
<td>0.319</td>
<td>3.8</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>20 MV Clinac 2300 C/D</td>
<td>6</td>
<td>0.103</td>
<td>0.303</td>
<td>3.8</td>
<td>2</td>
<td>25</td>
</tr>
</tbody>
</table>

\(^a\) No flattening filter for the cobalt unit.

and three-quarters of the points on all fields and energies have a percent difference of less than 14%.

From this figure, it appears that the model breaks down for the smallest and the largest fields (14% for 5 × 5 cm\(^2\) fields, 6% for 10 × 10, 8% for 15 × 15 cm\(^2\) fields and 17% for 30 × 30 cm\(^2\) fields). For example, the weakest agreement between calculations and measurements was observed for the Clinac’s 5 cm × 5 cm (the model underestimated the normalized dose by 20% and 13% at off-axis distances ranging from 15 to 20 cm) and 30 cm × 30 cm (the model overestimated the normalized dose by 40% at 30 cm) field size.

Figures 5 and 6 illustrate the ability of present modeling to handle simple shapes (figures 5(a) and (b)) and multi-leaf-designed complex-shaped fields (figures 6(a) and (b)).
Figure 4. Variation, according to distance from the field center, of measured and calculated out-of-field doses at 10 cm depth in a water tank, for different field sizes (cm²) and SSD set at 80 cm for cobalt treatment unit Alcyon II (a) and an SSD set at 100 cm for the Varian linear accelerators: Clinac 2300 C/D operated at 6 MV; (b) Clinac 2300 C/D operated at 20 MV RX; (c) and Novalis Tx operated at 6 MV (d). The doses are given as percentage of dose to dose at the depth of the maximal dose on the beam axis.
4. Discussion

We attempted to assess the suitability of multisource modeling for computations of out-of-field dose distributions related to linear accelerator head scatter and leakage radiation. This approach, introduced by Dunscombe and Nieminen (1992), has already been successfully used by several authors to study the field size dependence of relative output from linear accelerators (Dunscombe and Nieminen 1992, Yu and Sloboda 1995, Jian et al 2001, Yang et al 2002). By demonstrating that the mean difference between measurements and calculations may be less than 9% in out-of-field dose calculations, our work strongly suggests that multisource modeling could provide valuable assistance in developing modern out-of-field dose evaluation algorithms necessary for providing solutions to recent ICRU recommendations regarding the dose delivered to the RVR. This work also demonstrates the potential capacity of multi planar source modeling to accurately handle any complex shape field designed by modern medical linear accelerators equipped with multi-leaf collimators. It should also be noted that this approach can be adapted to a poly energetic beam by associating a different asymmetry parameter $g_i$ with each energetic component $E_i$ and consider the fluence weighted by the spectrum in equation (7). However, our results showed that the inclusion of a single energetic parameter $E_0$ was sufficient to obtain acceptable deviations from the experimental measurements.

Nonetheless, the validity of our semi-empirical modeling primarily depends on the accuracy of TLD measurements performed in order to establish estimates of the basic parameters $g$ and $\omega$. It had previously been established that overall uncertainty for TLD dose measurements in the Equal-Estro Laboratory using powder-type dosimeters under standard on-axis conditions was estimated as being in the range of 3.5 to 4.5% (2 SD) (Derreumaux et al 1995, Marre et al 2000, Ferreira et al 2000). In the present work, taking into account specific conditions due to off-axis measurements, additional uncertainties related to off-axis energy spectrum variation must be taken into account (Scarboro et al 2011). The overall uncertainty of dose measurements in off-axis conditions using a set of three TLDs was estimated to be about 10% (2 SD) for the lowest dose range. Uncertainty would probably be lower for higher doses.
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Figure 5. Calculated isodose for simple shaped fields (a) 10 × 10 cm² square field and (b) 10 × 20 cm rectangular field. Doses are given as percentage of the dose to the dose at the depth of the maximum dose on the beam axis. Calculations are made for Varian linear accelerator Clinac 2300 C/D operated at 6 MV RX.

5. Conclusions

The present work has shown that the total absorbed dose outside the beam path can be experimentally assessed as the sum of three separate constituent components: (1) the absorbed dose due to internal scattering originating within the patient; (2) the absorbed dose due to
Figure 6. Calculated isodose curves for complex shaped fields. The shapes of the fields are inserted top left on the pictures. Doses are given as percentage of dose to dose at the depth of the maximal dose on the beam axis. Calculations are made for Varian linear accelerator Clinac 2300 C/D operated at 6 MV RX.

external scattering originating in the treatment machine’s head and; (3) the absorbed dose due to external leakage also originating in the treatment machine’s head. The latter two components can be successfully modeled using the multisource approach if proper design of the extrafocal sources is established.
The applicability of the method for complex field shapes is demonstrated as well as providing applications to the IMRT modalities, which are becoming an increasing trend. IMRT is most often accompanied by increased monitor units (Ruben et al 2011), which are most often delivered via small field segments for which the out-of-field dose by head scatter and leakage plays an even greater role.

6. Future directions

A recent work (Howell et al 2010) demonstrated that, for tissues located about ten centimeters from the treatment field border, most current commercial treatment planning systems (TPS) used in radiotherapy departments for patient treatment planning may underestimate out-of-field doses by more than 50%. According to ICRU Report 83 (ICRU 2010), absorbed dose in the RVR might be useful for estimating the risk of deterministic effect related for example to the dose to the ovary or crystalline and late effects such as cardiovascular diseases, pulmonary fibrosis, second cancers, etc. Therefore, providing solutions for better estimations of out-of-field doses will have increasing clinical significance (choosing between different techniques depending on the radiation dose delivered to RVR for example) and their integration in TPS will soon become widespread. This work may be relevant to the concerns of modern radiotherapy due to its flexibility with regard to the machine’s geometry and its low computational cost.

Finally, several worldwide epidemiological publications (BEIR 2006, Xu et al 2008, NCRP report 170, De Vathaire 1999) have been devoted to the occurrence of second primary cancers among patients having received radiation therapy for primary cancers in childhood, adolescence, or as adults. There appear to be considerable uncertainties in the current second cancer risk models. To better assess the dose–response relationship, several studies have suggested that cancer risk is related to the inhomogeneous dose distribution across an organ rather than the average dose (Dasu et al 2005, Schneider et al 2005). However, these approaches require an accurate and patient-specific out-of-field dose reconstruction.

Our findings could then potentially impact the design of external beam radiotherapy patient-cohort-based epidemiological studies of radiation-induced late toxicity, notably for organs located at some distance from the beams.

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