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Original paper

Use of IAEA's phase-space files for the implementation of a clinical accelerator virtual source model

Alexis Rucci [a,b,*], Claudia Carletti [a,b], Walter Cravero [a,b], Bojan Strbac [c]

[a] *Instituto de Física del Sur, Universidad Nacional del Sur, Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Alem 1253, 8000 Bahía Blanca, Argentina*

[b] *Departamento de Física, Universidad Nacional del Sur, Av. Alem 1253, 8000 Bahía Blanca, Argentina*

[c] *International Medical Centres, Centre for Radiotherapy, Dvanaest beba bb, 78000 Banja Luka, Bosnia and Herzegovina*

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ABSTRACT

In the present work, phase-space data files (phsp) provided by the International Atomic Energy Agency (IAEA) for different accelerators were used in order to develop a Virtual Source Model (VSM) for clinical photon beams. Spectral energy distributions extracted from supplied phsp files were used to define the radiation pattern of a virtual extended source in a hybrid model which is completed with a virtual diaphragm used to simulate both electron contamination and the shape of the penumbra region. This simple virtual model was used as the radiation source for dosimetry calculations in a water phantom. The proposed model proved easy to build and test, and good agreement with clinical accelerators dosimetry measurements were obtained for different field sizes. Our results suggest this simple method could be useful for treatment planning systems (TPS) verification purposes.

Introduction

Monte Carlo (MC) methods have shown to be a reliable, accurate and practical approach for simulation of electron and photon beams used in clinical applications involving complex geometries [1–3].

Dose calculation applying MC methods is typically split into two parts. First, a detailed transport of the complete beam through the accelerator treatment head is carried out. Photon energy and spatial distributions in a clinical accelerator treatment head depend on its detailed structure. In order to achieve an acceptable level of accuracy, it is imperative to have detailed information on the shape and materials of the treatment head components through which radiation transport is simulated [4]. Usually, however, this information is not provided by the accelerators suppliers, or it is provided with insufficient detail to guarantee an accurate MC simulation of radiation transport through complete treatment heads. When detailed treatment head information is available and MC simulation for radiation transport through it can be performed, simulation output is usually stored into a phase space (phsp) file, in which each particle state (type, energy, position and direction) for a predefined plane is stored [5,6].

Radiation transport within the target (patient or water phantom) is then calculated using the previous phsp as the radiation source for a new MC simulation. A given phsp corresponds to a definite state for the accelerator head (primary beam type and energy, jaws aperture, other beam modifiers as included in the first step), and may correspond to different actual treatment fields, if patient position, gantry position, etc, are changed. Thus, dosimetry corresponding to different targets may be calculated using the same phsp file. The precise plane at which the phase space state is scored may vary depending on the treatment requirement. Applicators, multileaf collimators, compensators, and different tray accessories placed between the jaws and the clinical target may be included as part of the target or the treatment head as best suited. In general, voxelized geometry is suitable for the patient simulation, whereas simpler geometry is used in some Monte Carlo codes (e.g., quadric surfaces are used in PENELOPE) for structure delimitation in the treatment head, and those requirements may constrain the phsp scoring plane position [7,8].

* Corresponding author. Instituto de Física del Sur, Universidad Nacional del Sur, Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Alem 1253, 8000 Bahía Blanca, Argentina.

E-mail addresses: alexisrucci@gmail.com, alexis.rucci@uns.edu.ar (A. Rucci).

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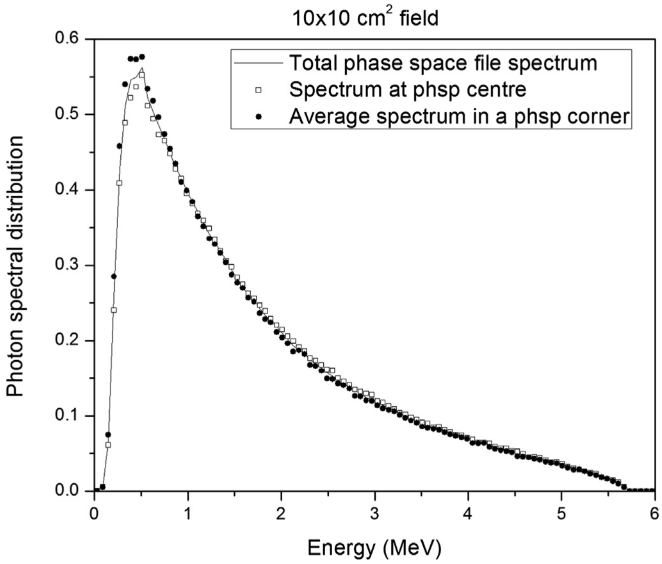

Figure 1. Photon spectra for a 6 MV and 10 × 10 cm^2 field, corresponding to a Varian Clinac iX accelerator at the water phantom surface, obtained from the IAEA's phsp data. Continuous line: photon energy spectrum from the entire scoring square. Filled circle: idem for photons taken from a 1 cm^2 square at each of the phsp scoring square corners. Hollow square: Spectrum from a 1 cm^2 square at the center of the phsp scoring square.

Considering the statistical uncertainties related to the stochastic nature of radiation transport processes, huge phsp files are needed in order to take account of the primary beam physical properties as well as the effect of the structures in the accelerator head [9,10].

The International Atomic Energy Agency (IAEA) started to work on a phase space databank a few years ago (http://www-nds.iaea.org/phsp/phsp.htmlx). The aim of this project is to establish a freely available public database of phsp data for clinical accelerators and ^{60}Co units used for radiotherapy applications, easing the access to several photon and electron beams for each specific machine. Phsp files in the databank contain the detailed description of the scored particles. IAEA's phsp files should provide information about position, direction, kinetic energy, statistical weight, type and storage information of each scored particle. IAEA format also takes into account the possibility that an accelerator source is simulated with a so called *event generator* that mimics the treatment source using either a full Monte-Carlo simulation or a beam model of the radiation therapy source [11]. A review process is carried out on submitted phsp data before acceptance into the database. Consistency checks and experimental validation is required for submitted phsp data, and range of applicability must be documented by submitters [11]. IAEA has committed to the provision of subroutines to read and write IAEA-format binary files. Conversion routines exist for commonly available simulation packages (MCNP, EGS, PENELOPE, etc.) [12,13].

Phsp data are usually tallied at the surface of a water phantom, a useful position for commissioning or verification albeit not practical if we want to simulate a complete treatment that includes other beam modulators, starting from these phsp files.

Absorbed dose will depend on the initial energy spectrum for primary photons as well as secondary particles generated both in the accelerator head and the target. It is possible, however, to build a system able to simulate the same energy deposition without explicitly taking into account the original accelerator head geometry. This technique is known as virtual source model (VSM), and its main advantage is that the process is faster than the classical MC simulations and the number of histories doesn't depend on the size of the phase space data [9,14–17]. VSM development implies the optimization of several parameters in order to obtain a good enough approximation to the dose deposition obtained with the complete MC transport. These include position of each virtual source (also shape and density distribution in case of extended sources), energy distribution, etc. Some models include primary photons, secondary photons and electron contamination sources [17,18]. When the number of VSM variables is too long, optimization becomes cumbersome, and we may end replacing a complicated geometric problem with a complicated optimization one.

An intermediate approach involves replacing the accelerator head by a combination of virtual sources and simplified geometrical structures through which radiation is transported. This kind of method is called *hybrid model* [19]. It could be very useful if applicators or MLC were to be added to the treatment simulation. A realistic VSM needs to take into account the contribution from electron contamination. However, the electron contamination source can be replaced, in a hybrid model, by a simple structure which generates it.

Based on the IAEA phase space data for external radiotherapy beams, we have made dose calculations for different field sizes and

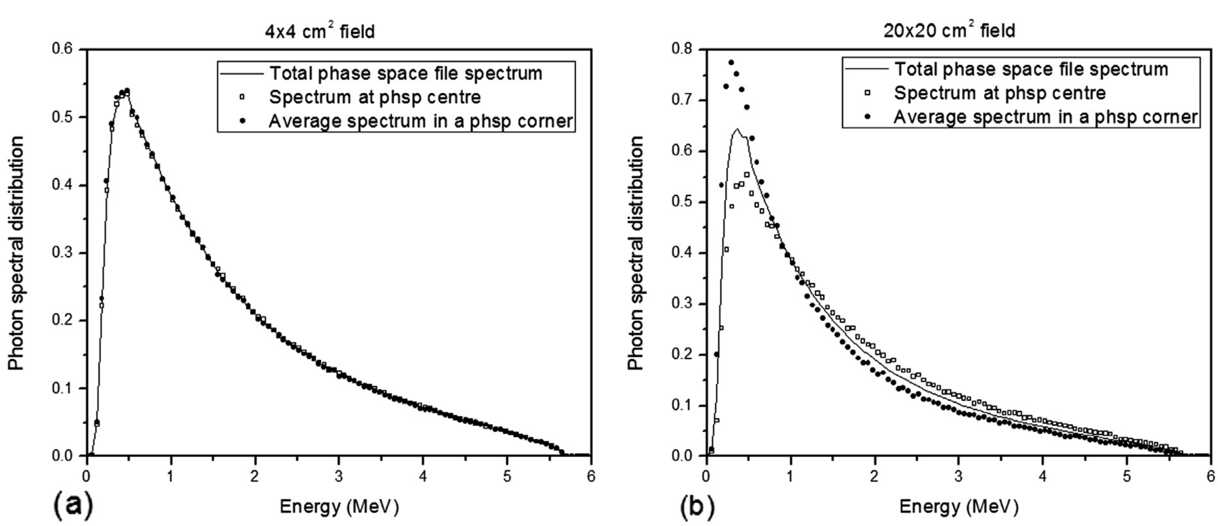

Figure 2. Idem Fig. 1 for (a) 4 × 4 cm^2 field and (b) 20 × 20 cm^2 field.

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beam energies. Particularly, we have used IAEA phsp files corresponding to Varian Clinac iX and Siemens Primus accelerators, in order to extract the photon spectra. From these, virtual photon sources were set-up for dose distribution simulations in a water phantom. An ad-hoc diaphragm was added to the model in order to define the field size (and its penumbra), as well as to include electron contamination, as normal jaws would perform in an actual accelerator. Using this VSM, we have calculated dose profiles and percent depth doses (PDDs) for several field sizes. All MC calculations were done using the radiation transport code PENELOPE [20]. The results were compared with those obtained from the original IAEA's phsp as well as experimental measurements for a Varian Clinac iX and for both accelerator models.

Materials and methods

Experimental setup

The experimental results were obtained using the Varian Clinac iX accelerator from the International Medical Centre in Banja Luka, Bosnia and Herzegovina. PDDs were measured for open fields. We used a remotely controlled water phantom MULTIDATA (Universal 3D water phantom 9850 48 × 48 × 41.5 cm^3) and a small volume ionization chamber (All-purpose Multidata 9732-2 thimble ion chamber0.125 cm) with holders included in all RTD water phantom systems [21]. The PDD has been collected for several square field sizes, from the smallest to the largest available, as well as for some rectangular fields at the standard Source to Surface Distance (SSD = 100 cm). Scanning starts with the detector at the deepest possible position and moving toward the surface, possibly overshooting the origin by a few millimeters. This procedure minimizes the effect of water ripples and gives an independent check on the position of the surface where the PDD will abruptly change gradient. The depths, at which the profiles were scanned, were determined by the requirements of the treatment planning system in the service, and they included the depth of maximum dose and the deepest possible position of the detector in the tank. The scan width is a function of both the field size and the depth (due to the beam divergence) and it is large enough to include not only the beam edges but also at least 5 cm beyond the geometrical edge of the beam.

Table 1
Best values for the parameters needed in equations (1) and (2).

Parameter	Best value
α_1	2.5 ± 0.1 cm^{-1}
α_2	5.5 ± 0.2 cm^{-1}
t	0.010 ± 0.003
p	0.80 ± 0.02 cm

Virtual source from IAEA's phsp

In IAEA's database, phsp files for photons are usually scored at or close to the surface of a water phantom. This is useful, for example,

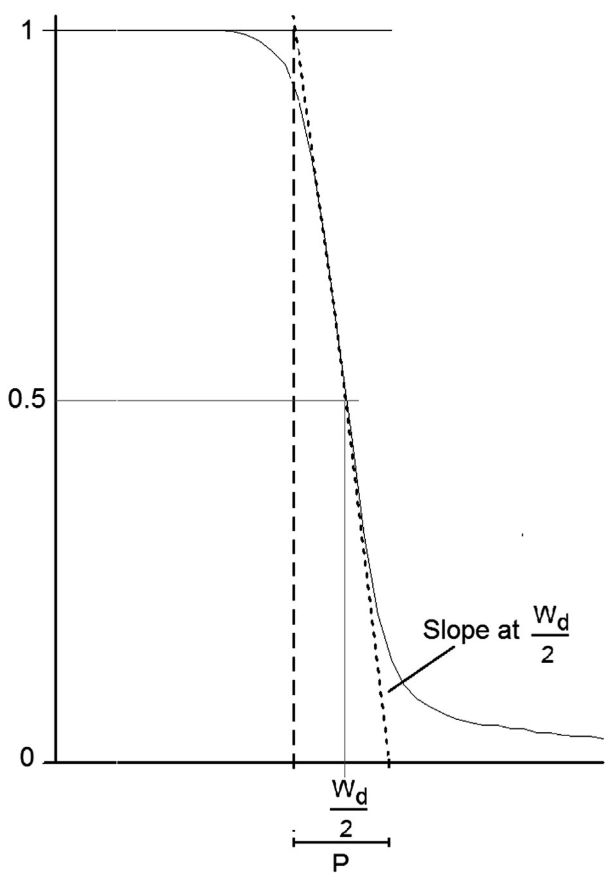

Figure 3. Scheme for the determination of penumbra width.

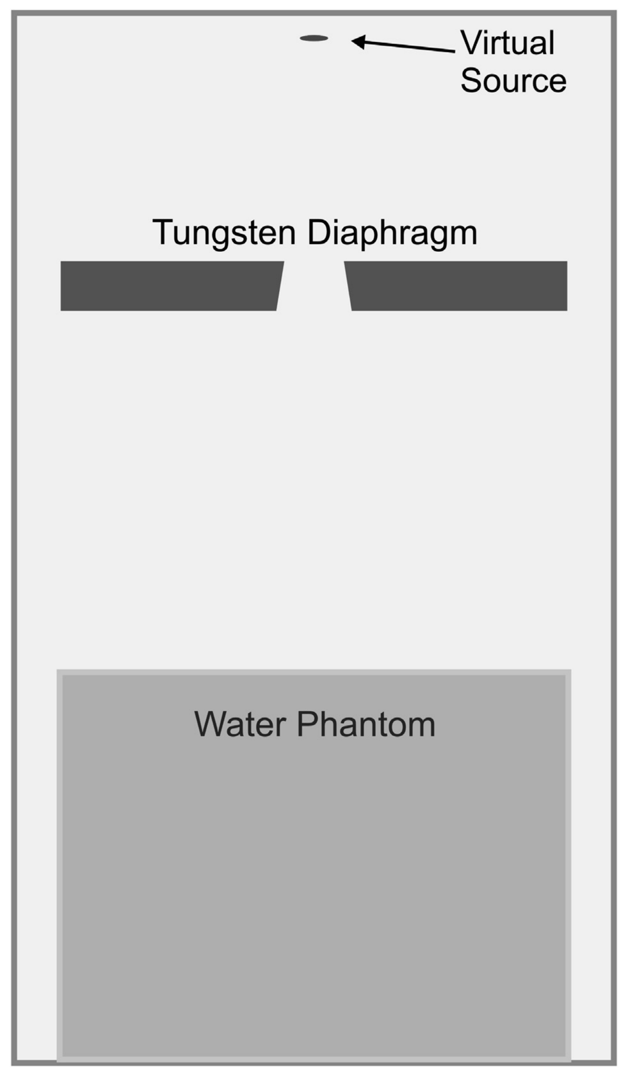

Figure 4. Virtual source model scheme used in the simulations.

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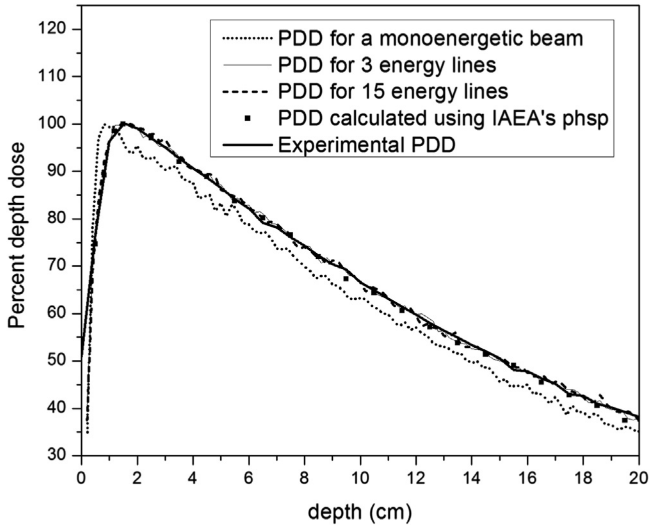

Figure 5. Comparison between original phsp, VSM, and experimental PDDs for a Varian Clinac iX accelerator, 10 × 10 cm^2 field.

in clinical accelerator calibration procedures. However, if our interest lies in developing an alternative method of treatment planning verification, phase space data become impractical as each time a modification in the head accessories is introduced, a complete new MC simulation must be run. Building a virtual source model for the accelerator using IAEA phsp data may be a suitable way to overcome this drawback.

As a first step to define such a model, three phsp files for a Varian Clinac iX, for a 6 MV 4 × 4, 10 × 10 and 20 × 20 cm^2 fields at SSD = 100 cm were considered [22]. For 4 × 4 and 10 × 10 cm^2 fields (20 × 20 cm^2 field), 1 × 10^8 (5 × 10^7) original histories were simulated. BEAMnrc code was used for the original calculation using a monoenergetic electron source of 5.7 MeV at the accelerator exit window. Transport parameters for all fields are 0.7 MeV of cutoff energy for electrons, 0.01 MeV of cutoff energy for photons, a maximum step-size for electron transport (SMAX) of 5.0 cm, a maximum fractional energy loss per step (ESTEPE) of 0.25 and a maximum first elastic scattering moment (XIMAX) of 0.5. Calculated latent variance for the obtained phase spaces is 0.08%.

We extracted energy distributions from the phsp data using the *derive spectral distribution from ph-sp data* tool in the beamdp GUI application of the EGSnrc code [23]. In order to estimate the spectral homogeneity of the phsp, we compared the photon energy distribution in different regions of 1 cm^2 area of the phsp file with spectra averaged over complete scoring plane. Distributions are practically identical for the considered fields, except for the larger 20 × 20 cm^2 field (see Figs. 1 and 2). In this last case, from centre to corner, mean energy decreases 6%, energy variance decreases 2% and skewness decreases 10%. This reflects the well known fact that, for larger fields, the accelerator flattening filter induces variations in energy distribution as well as in particle spatial density.

The proposed VSM consists of an extended virtual source and a diaphragm, which delimitates the size of the field and generates electron contamination. The diaphragm was set at the usual position of the head jaws in a treatment accelerator (Fig. 4).

The virtual source energy spectrum is the superposition of an integer number of monoenergetic sources. We evaluated both PDDs and cross profile doses, for discrete energy distributions with 1, 3 and 15 energy lines respectively. The weight and energy position of the spectral lines were calculated taking into account the mean energy and, for 3 and 15 lines, higher moments of the continuous energy distribution from the phsp data.

For 3 and 15 energy lines, the simulated PDDs and cross profiles obtained with our VSM, match remarkably well those directly calculated using the phsp, as well as experimental data, while, as expected, a single monoenergetic beam does not yield acceptable results (Fig. 5). Thus, in order to simplify and speed up the MC simulation without significative accuracy loss, we considered in the rest of this work a VSM with only three lines at 1 MeV, 3 MeV and 5 MeV with a relative weight of 68.37%, 25.04% and 6.59% respectively. These weights are calculated so that mean energy, variance and skewness of the continuous spectrum is matched.

In dose calculations for clinical applications it is important to take proper account of the field penumbra. Here we use penumbra width in order to obtain the virtual source size. We fitted an experimental 10 × 10 cm^2 and 6 MV cross profile for a Varian Clinac iX with the mathematical function *f(x)* where

$$f(x) = \begin{cases} 1 - 0.5e^{-\alpha_1\left[\frac{W_d}{2}-|x|\right]} & for\ \ |x| \le \frac{W_d}{2} \\ t + (0.5-t)e^{-\alpha_2\left[|x|-\frac{W_d}{2}\right]} & for\ \ |x| > \frac{W_d}{2} \end{cases} \quad (1)$$

and x is the position; $W_d/2$ is half the width of the beam at depth d, α_1 and α_2 are empirical constants and t is the effective transmission through the collimator [24]. We estimated p through the intersection of each *f(x)* branch slope (calculated at $W_d/2$) with the

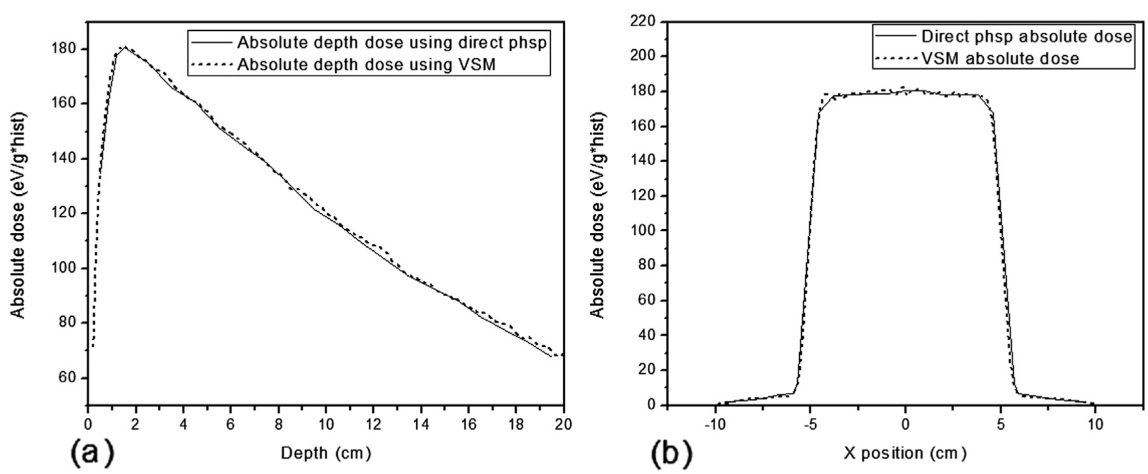

Figure 6. Absolute depth dose (a) and cross profile at dose maximum depth (1.6 cm) (b), for VSM and original IAEA phsp for Varian Clinac iX accelerator. Field size: 10 × 10 cm^2.

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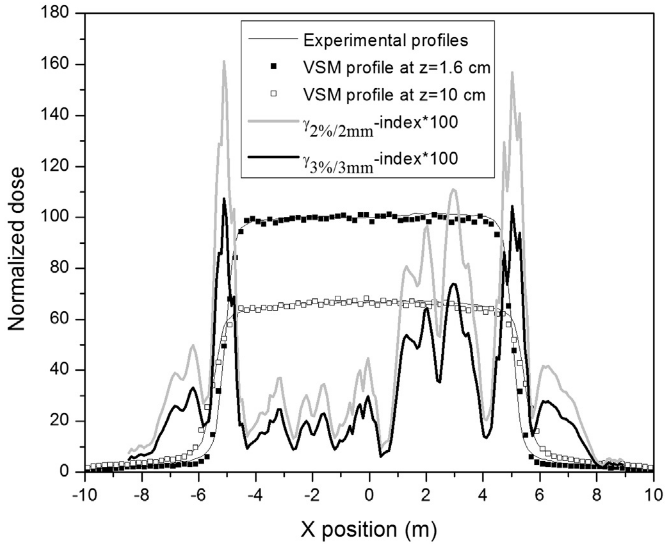

Figure 7. Cross profiles comparison between the VSM and experimental for a depth of 1.6 cm and 10 cm. Field size: 10×10 cm^2.

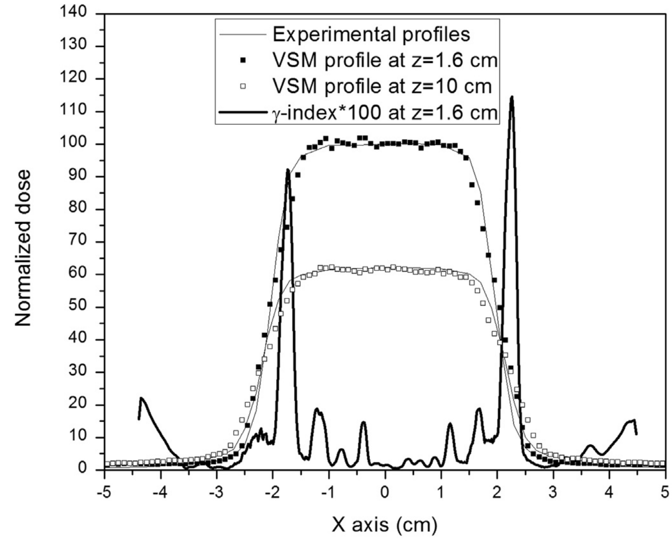

Figure 9. Idem Fig. 7 for a 4×4 cm^2 field size. γ index was calculated using 3%/3 mm criterion.

horizontal lines corresponding to maximum and zero normalized doses (see Fig. 3). Eventually, it would also be possible to use the cross profile data simulated from the original phsp file, instead of the measured ones.

Best values for fitting parameters α_1, α_2 and t and the derived p value are shown in Table 1.

From p we calculate the source width s using the geometric penumbra formula:

$$p = \frac{s(f - f_1)}{f_1} \qquad (2)$$

where f_1 is the distance from the source to the collimator and f is the source to phantom surface distance (SSD).

We made a box shaped source with effective dimensions of $s \times s \times 0.05$ cm^3, with $s = 0.5$ cm. Equivalent cylindrical sources were also tested and similar results obtained. Source divergence was set to 5° for 10×10 cm^2 field or smaller, and 10° for larger fields. We considered an homogeneous particle distribution in the source, although more sophisticated distributions are of course possible, (and should be used for large fields).

A scheme of the VSM is showed in Fig. 4. The 5 cm thick diaphragm has a variable opening to change the field size, and its upper surface was located at 30 cm from the source. The material (tungsten) was selected because it is the usual composition of the jaws in an accelerator head, and the thickness was chosen so that transmission through the diaphragm fits data beyond the penumbra region. In a Varian Clinac iX the thickness of the jaws is 7.5 cm.

Dose deposition was calculated in a $40 \times 40 \times 40$ cm^3 water phantom. We used 1×10^9 histories in the VSM calculations. Statistical uncertainty for these calculations is approximately 0.5%. Voxel side for spatial dose distributions in all calculations was 2 mm except for 4×4 cm^2 field, in which case 1 mm voxel side was used.

Results and discussion

In Fig. 5 we show the PDD for a 10×10 cm^2 field and 6 MV corresponding to a Varian Clinac iX accelerator. We compared

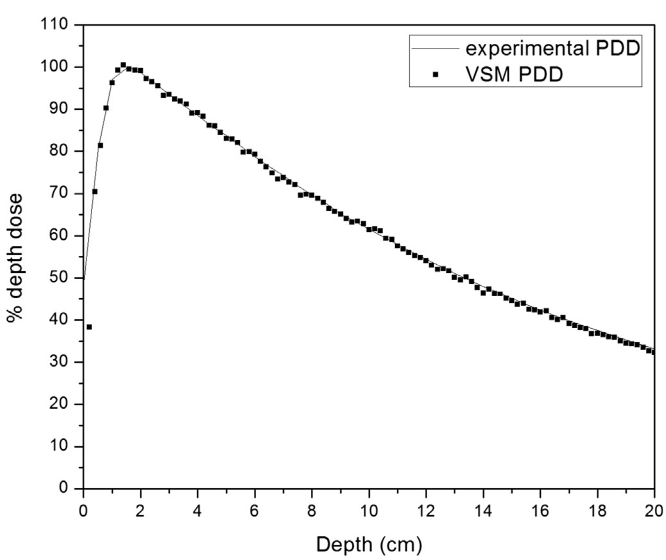

Figure 8. Idem Fig. 5 for a 4×4 cm^2 field size, VSM calculations vs. experimental data.

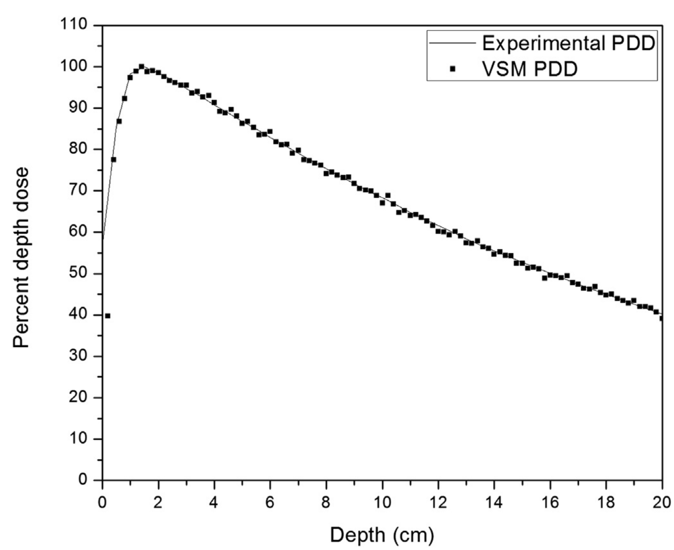

Figure 10. Idem Fig. 5 for a 15×15 cm^2 field size.

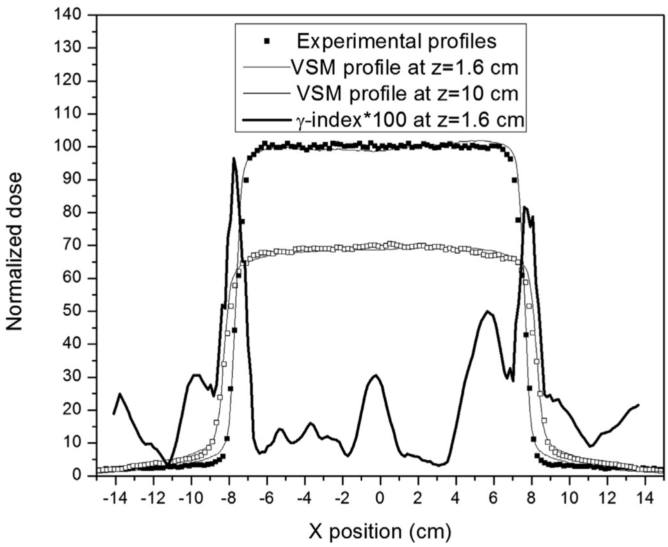

Figure 11. Idem Fig. 7 for a 15 × 15 cm^2 field size. γ index was calculated using 3%/3 mm criterion.

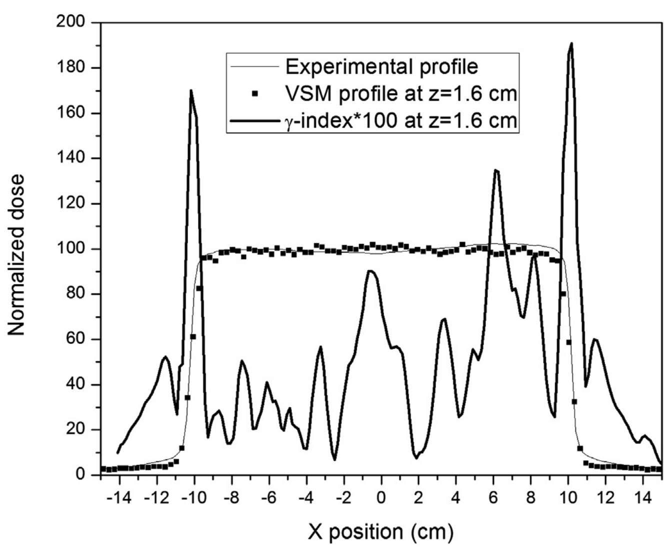

Figure 12. Cross profiles comparison between VSM and experimental for a depth of 1.6 cm, for a 20 × 20 cm^2 field size. γ index was calculated using 3%/3 mm criterion.

original IAEA phsp calculations with experimental results and VSM using 1, 3 and 15 energy lines.

We performed absolute dose comparison between the original IAEA phsp and VSM (3 energy lines). We obtained very good agreement both for depth and cross profiles results (Fig. 6).

In Fig. 7 we show normalized cross profiles for the same field at 1.6 cm and 10 cm depth for experimental and VSM calculations. The figure also shows the gamma index for 1.6 cm profile. 99% of the points have a $\gamma_{3\%/3mm} < 1$, while 90% have a $\gamma_{2\%/2mm} < 1$ [25,26].

Using the same spectrum obtained for the, we changed the aperture of the diaphragm in order to simulate a 4 × 4 cm^2 and 15 × 15 cm^2 fields. The fact that a phsp derived for the 10 × 10 cm^2 field could be used (with good results) for different field sizes and the same nominal energy is due to the high degree of photon spatial homogeneity in the IAEA's phsp for 10 × 10 cm^2 field.

Figures 8 and 9 show results for small fields (4 × 4 cm^2) while Figs. 10 and 11 show the results for larger fields (15 × 15 cm^2). In order to ease comparisons, all cross profiles were normalized at maximum dose position, i.e., at 1.6 cm for a 6 MV beam. We used 1 × 10^9 histories in all simulations. In all cases 99% of the points have a $\gamma_{3\%/3mm} < 1$. We also performed calculations for 20 × 20 cm^2 shown in Fig. 12. Even in this case, 91.5% of points have $\gamma_{3\%/3mm} < 1$. As field size increases, use of a single virtual source derived from a 10 × 10 cm^2 field is set to yield less accurate results, as inhomogeneities in the energy spectrum of the 20 × 20 cm^2 phase space, are not taken into account in our source model.

In view of the good agreement obtained between the VSM and the experimental data, we made simulations for PDDs and cross profiles for a 10 × 10 cm^2 field and energy of 6 MV for a Siemens Primus accelerator, comparing the EGSnrc calculation with the IAEA's phsp and the same calculation performed with our VSM. These results are showed in Fig. 13(a) and (b). In this case, the number of histories in the calculation with the IAEA's phsp is limited to the size of the phase space file provided (1.5 × 10^7 histories). For the VSM calculations, we used 1 × 10^9 virtual primary particles.

Calculations made with IAEA's phsp was carried out recycling 8 times the phsp. This file has a latent variance of 0.11% (relative error) and in the simulations we reached an uncertainty of 0.14% [27]. Gamma analysis between our model and calculations with the original phsp file shows that 100% of points have a $\gamma_{3\%/3mm} < 1$, and 96% have a $\gamma_{2\%/2mm} < 1$. It is to be noted that while we compared VSM with experimental data in the case of the Varian accelerator, in the case of the Siemens Primus we are just comparing both theoretical calculations.

Our results suggest that IAEA phsp files can be used as the starting point of a virtual source model. Good agreement is

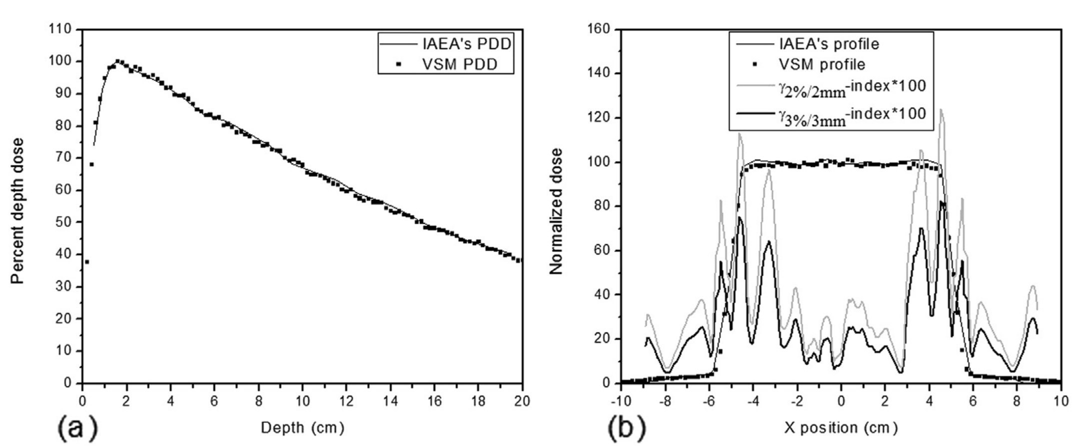

Figure 13. PDDs (a) and cross profiles (b) comparison between IAEA's phsp and VSM for a Siemens Primus accelerator.

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obtained between VSM calculations and measured data and between VSM calculations and those performed using original phsp files. As field size increases a more detailed analysis of the photon distribution is necessary in order to take into account the beam modification by the flattening filter.

Conclusions

In this work we have implemented a virtual source model for clinical photon beams based on the phsp obtained from the IAEA's phsp database for radiotherapy accelerators. We have calculated PDDs and cross profiles for different field sizes for a standard water phantom. Our model is based on spectral and spatial analysis of the original phsps from which the VSM is defined. Although different virtual sources can be defined from the information available, our aim was to keep the model as simple as possible and then no attempt was made to implement a full optimization scheme at this stage.

We compare our VSM with calculations made using the phsp files for two accelerator models from IAEA database and, for a Varian Clinac iX, with available experimental data.

Performance of VSM was assessed using gamma index analysis showing an acceptable agreement with experimental data within the 3%/3 mm criterion for practically the whole range, and within 2%/2 mm for all the high dose region, in all cases except the largest field size considered (20×20 cm^2) [28–32].

VSM method amounts to the definition of an event generator from the available phsp, or a splitting scheme for variance reduction in which a statistical analysis of the phsp is performed. In this paper we made a rather crude analysis of the phsp energy spectrum and spatial distribution. However, this is enough to extract the relevant physical characteristics of the impinging beam, at least for the field sizes considered.

The main advantage of the VSM over an splitting or recycle scheme applied to the original IAEA phsp lies in the fact that once a suitable VSM is defined, shaping beam structures such as MLC could be easily added below the diaphragm. As IAEA phsp files are scored at or near the phantom surface (which is OK for calibration purposes), they are not a suitable source for actual MC treatment planning. The aim of a simple VSM like the one we analyzed here is not direct treatment planning, but its suitability as an independent treatment planning verification system. The availability of reliable phsp files for different accelerator models from IAEA coupled to a VSM that can be built from them, could remove one of the biggest problems in building a MC based treatment planning verification scheme, i.e., the scarcity of information on the treatment head detailed geometry and materials for different accelerator models.

Acknowledgments

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