Physica Medica 32 (2016) 1030–1033

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Technical note

Use of IAEA's phase-space files for virtual source model implementation: Extension to large fields

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ARTICLE INFO

Article history:
Received 1 December 2015
Received in Revised form 7 July 2016
Accepted 10 July 2016
Available online 14 July 2016

Keywords:
Radiotherapy
Monte Carlo
Phase-space
IAEA
Virtual source
Large fields

ABSTRACT

In a previous work, phase-space data files (phsp) provided by the International Atomic Energy Agency (IAEA) were used to develop a hybrid virtual source model (VSM) for clinical photon beams. Very good agreement with dosimetric measurements performed on linear accelerators was obtained for field sizes up to 15 × 15 cm^2. In the present work we extend the VSM to larger field sizes, for which phsp are not available. We incorporate a virtual flattening filter to our model, which can be determined from dose measurements for larger fields. In this way a fully functional VSM can be built, from publicly available IAEA's phsps and standard dose measurements, for fields of any size and tailored to a particular linac.

1. Introduction

General Monte Carlo (MC) methods have been used for a long time as a standard research tool for the simulation of ionizing radiation transport through material systems that exhibit complex geometry and/or composition. Such methods are well suited for dosimetry calculation in medical physics [1–3].

In a previous publication [4], we have shown how to build a VSM for linac simulation starting from phsp files provided by the IAEA, to which we refer the reader for a detailed description. Very good agreement was found with measured cross profiles and PDDs for field sizes up to 15 × 15 cm^2.

When larger field sizes are considered, VSM performance worsens as decreasing spatial homogeneity in the corresponding phsp file is not taken properly into account in the VSM, which essentially uses the phsp spatially averaged energy distribution. Besides, IAEA's present database does not include phsp files for field sizes larger than 20 × 20 cm^2 [5]. This is probably due to the fact that validation requirements for phsp files are, generally, more difficult to achieve for larger fields.

In this work we show how an extension of the VSM can be built, in order to include large field sizes, adding a virtual flattening filter (VFF), determined with the help of standard dose measurements.

2. Materials and methods

2.1. 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 of different sizes. 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 chamber 0.125 cm^3) with holders included in the RTD water phantom systems [6]. Experimental data for 20 × 20 cm^2, 30 × 30 cm^2 and 40 × 40 cm^2 fields are used in this work.

2.2. Virtual source from IAEA's phsp

All calculations were performed using the PENELOPE MC code [7]. We used a cut-off energy of 1×10^5 eV for electrons and 1×10^4 eV for photons. No variance reduction technique was used and scoring volume was 0.027 cm^3. Number of histories was chosen so that MC statistical uncertainty was kept below 2%.

As in our previous model, a box shaped primary source with effective dimensions of 0.3 × 0.3 × 0.05 cm^3 was considered. Energy spectrum was defined as a superposition of three monoenergetic sources with energies of 1 MeV, 3 MeV and 5 MeV and

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http://dx.doi.org/10.1016/j.ejmp.2016.07.006

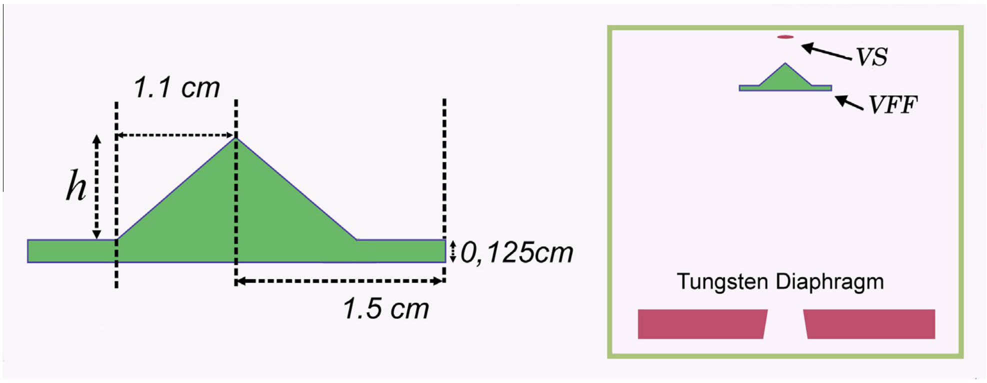

Fig. 1. Scheme of the flattening filter added to the virtual source model.

probabilities of 76.36%, 19.36% and 4.28%, respectively, obtained from a IAEA's phsp for a 20 × 20 cm^2 field, which is the largest available for this accelerator model.

When field sizes larger than 20 × 20 cm^2 are considered, photon spectral distribution changes as we move out of the beam axis towards the edges of the phase space scoring plane. In our case, photon mean energy extracted from the IAEA's phsp for the 20 × 20 cm^2 field decreases 6% from field centre to corner, while energy variance decreases 2% and skewness decreases 10% [4]· This reflects the well-known fact that the accelerator flattening filter hardens as well as depletes the photon beam at the centre of the field. In order to maintain a good agreement as the field size increases, the effect of the flattening filter must be better taken into account in our model. However, the inclusion of a proper or "physical" flattening filter in the VSM would not be correct if we still want to base it on IAEA's phsps. These files contain particle distribution for beams that have already passed through the FF of the accelerator [8]. Should the accelerator FF material and geometry be known, its effects on the photon beam could in principle be discounted. Here we pursue a different (and simpler) approach instead. Photon fluence passing through the thinnest part of the FF is less affected. So, we propose to extract the photon energy distribution from the spatial periphery of the phsp corresponding to the largest available field, i.e., 20 × 20 cm^2.

We used this energy distribution to build the primary virtual source. We then added a virtual flattening filter (VFF) to take again into account the full FF effect on the beam. This VFF has to be determined from simple dose measurements corresponding to the considered field size [9–12]. In our case we chose to use a simple copper-made VFF modelled with a circular cone of 1.1 cm radius and a variable height (which will be the fitting parameter), on top of a circular cylinder of 1.5 cm radius and 0.125 cm thickness (Fig. 1). The VFF base was placed at 12.5 cm from the primary virtual source [13].

To determine the cone height, we used the ratio between maximum dose (D_0) and central axis dose (D_i) calculated at maximum dose depth (in our case, 1.6 cm), as a function of the VFF height. We then used D_i/D_0 from measured cross profiles to determine the best VFF height.

Once we have redefined the VSM with the addition of the VFF, we performed simulations of 20 × 20 cm^2, 30 × 30 cm^2 and 40 × 40 cm^2 photon fields, and compared them with dose measurements in photon fields of the same field size.

3. Results and discussion

Calculated ratio D_i/D_0 as a function of VFF height is shown in Fig. 2. For a VFF free field, maximum dose is at the central axis, so $D_i/D_0 = 1$. D_i/D_0 was fitted with a simple exponential function $\frac{D_i}{D_0} = e^{-0.0378\ \mathrm{mm}^{-1}\ h}$, with h expressed in millimetres.

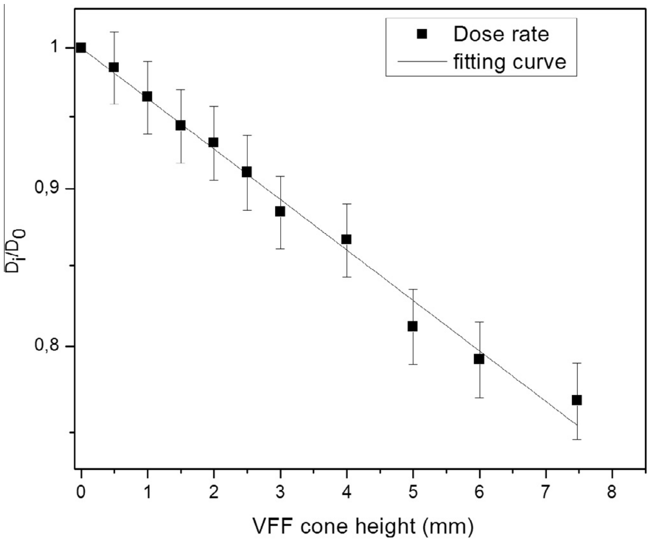

Fig. 2. D_i/D_0 in $\log_{10}$ scale vs flattening filter height and fitting curve.

In Fig. 3 we show the PDD for a 20 × 20 cm^2 field and 6 MV corresponding to a Varian Clinac iX accelerator and the present VFF tailored to the same machine. The VFF cone height obtained from the curve in Fig. 2 and the measured D_i/D_0 is in this case 0.81 mm, with a difference of about 3% between the maximum and minimum dose value in the low gradient region for the measured cross profile. MC statistical uncertainty was in this case about 1.25%. We found that $\gamma_{3\%/3\mathrm{mm}}$ for the entire range is less than 1.

In Fig. 4, normalized cross profiles for the same field, at 1.6 cm and 10 cm depth for experimental and VSM calculations are shown. Good agreement is found, with 95% of the points having a $\gamma_{3\%/3\mathrm{mm}} < 1$ at 1.6 cm depth, while 100% have a $\gamma_{3\%/3\mathrm{mm}} < 1$ at 10 cm depth [14,15].

Comparing the results of our VSM using VFF with that obtained in our previous publication (without VFF), we see that, in the high dose region, 100% of the points now verify the $\gamma_{3\%/3\mathrm{mm}} < 1$ criterion, whereas in the previous model, 5% of the points did not complied with it [4].

Using the same photon spectrum obtained for the 20 × 20 cm^2 field, we changed the aperture of the diaphragm in order to simulate a 30 × 30 cm^2 and 40 × 40 cm^2 fields.

For the 30 × 30 cm^2 field size, the uncertainty reached in the simulation was approximately 1.2%. The VFF was the same as in

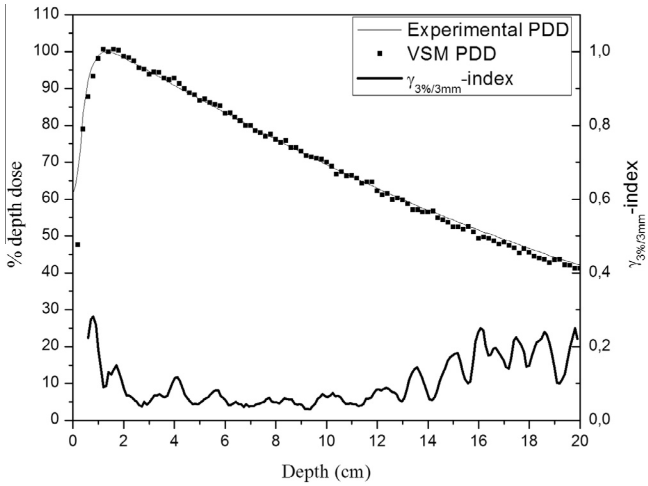

Fig. 3. Comparison between VSM and experimental PDDs for a Varian Clinac iX accelerator, 20 × 20 cm^2 field.

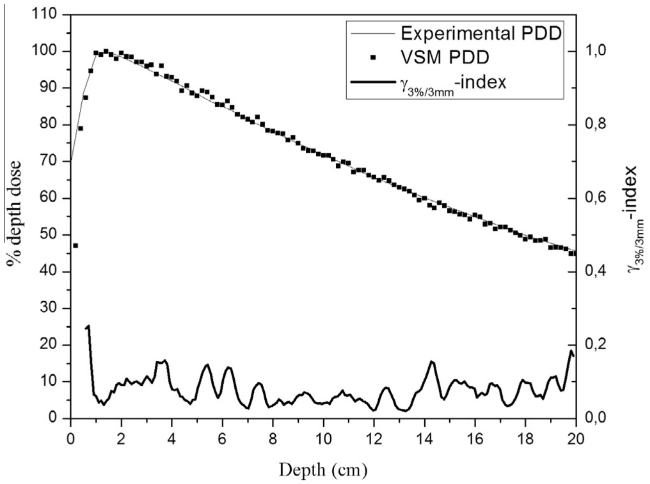

Fig. 5. Idem Fig. 3 for a 40 × 40 cm^2 field size, VSM calculations vs. experimental data.

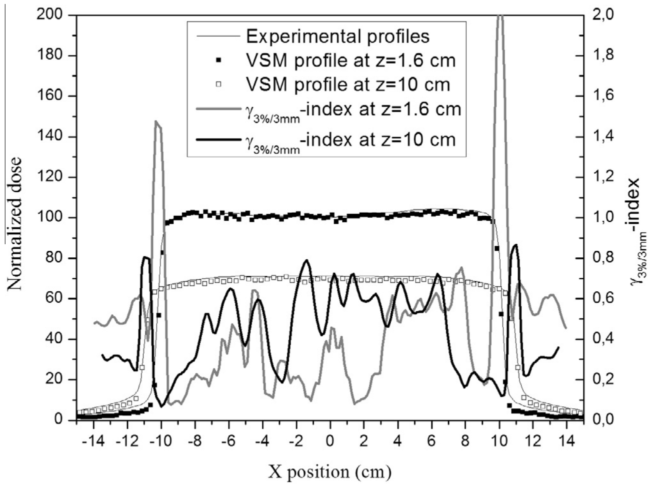

Fig. 4. Cross profiles comparison between the VSM and experimental for a depth of 1.6 cm and 10 cm. Field size: 20 × 20 cm^2.

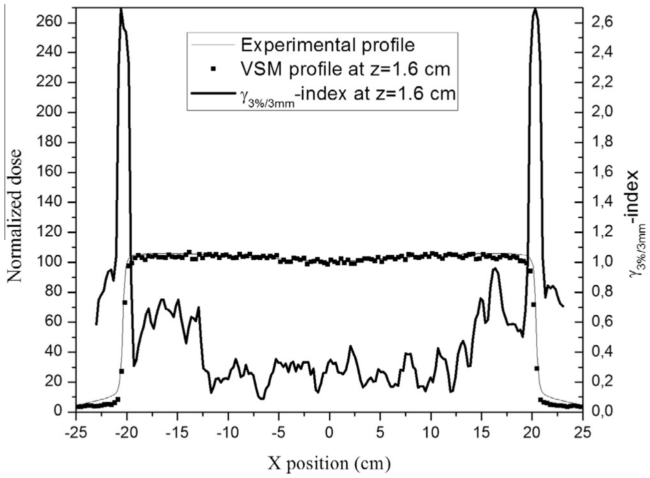

Fig. 6. Cross profiles comparison between the VSM and experimental for a depth of 1.6 cm. Field size: 40 × 40 cm^2.

the 20 × 20 cm^2 field. In this case, comparison shows 95% of the points have a $\gamma_{3\%/3mm} < 1$ in the cross profile at 1.6 cm depth, while 97% have a $\gamma_{3\%/3mm} < 1$ at 10 cm depth.

For the sake of brevity, in Figs. 5 and 6, PDDs and cross profiles corresponding to the largest field considered (i.e., 40 × 40 cm^2) are shown. In this case, MC calculation achieved an uncertainty of about 2%. At 1.6 cm depth, the difference between the measured dose at the centre of the cross profile and maximum dose was 6%. The corresponding VFF height for the MC simulations was set in 1.64 mm. We found that 94% of the points have $\gamma_{3\%/3mm} < 1$, with 100% of the points in the high dose region reaching $\gamma_{3\%/3mm} < 1$.

We found that VSM and experimental results are in very good agreement in the high dose region with 100% of points verifying the $\gamma_{3\%/3mm} < 1$ criterion. We also calculated output factors (OF) for all three simulated fields, and compared them to experimental ones. In all cases differences are within 3%.

Largest discrepancies between VSM and experimental results are observed in the region of high dose gradient and close to the phantom surface. Several factors may contribute to this, including the fact that electronic contamination is not fully taken into account in our virtual source model, even when "physical" structures such as diaphragms and VFF are added [16–18]. However, we note that the agreement in the penumbra region rapidly improves as depth increases, quickly reaching $\gamma_{3\%/3mm} < 1$ for depths beyond that corresponding to maximum dose.

Our VFF has to be considered as an additional shaping device, which allows us to use information from the measured field to modify a simulated beam originally calculated for a different field size. In this way we can extend the range of use for IAEA phsp data base to larger field sizes [19–21]. Moreover, we get a complete new phase space at jaws level for these fields from which complete MC simulations can be performed, in principle, for any accelerator included in the IAEA phsp data base. The small price we pay is to perform a single cross profile dose measurement at maximum dose depth for each desired field size. However, these are routine measurements in any radiotherapy facility.

4. Conclusions

In this work we have extended a VSM based on phsp files obtained from the IAEA's phsp database for radiotherapy accelerators to the calculation of large fields. We have developed a simple procedure that allows the determination of a single parameter VFF from standard cross profile measurements.

The main feature of our improved VSM is that we can now get a new phase space at the diaphragm level for any field size and any accelerator included in the IAEA's database. This means any additional shaping structure, such as a MLC, can be easily added below the diaphragm for dosimetry calculation purposes.

The intended use of this VSM is not, at this stage, direct treatment planning simulation. However, it can serve as a validated platform upon which a MC based independent TPS verification system can be built. The availability of reliable and validated phsp files for different accelerator manufacturers and models from IAEA coupled to a flexible and simple VSM that can be built using these phase spaces and standard routine dosimetric measurements provides a promising starting point for such a system.

Acknowledgments

This work has been partially supported by Universidad Nacional del Sur, Argentina under PGI 24/F062 and Agencia de Promoción Científica y Tecnológica under PICT 2007 red 1907.

References

[1] Mackie TR. Applications of the Monte Carlo method in radiotherapy. Dosim Ionizing Radiat 1990;3:541–620.

[2] Andreo P. Monte Carlo techniques in medical radiation physics. Phys Med Biol 1991;36(7):861–920.

[3] Chaves A, Lopes MC, Alves CC, Olivera C, Peralta L, Rodrigues P, Trindade A. A Monte Carlo multiple source model applied to radiosurgery narrow photon beams. Med Phys 2004;31(8):2192–204.

[4] Rucci A, Carletti C, Cravero W, Strbac B. Use of IAEA's phase-space files for the implementation of a clinical accelerator virtual source model. Phys Med 2014;30(2):242–8.

[5] Capote R, Jeraj R, Ma CM, Rogers DWO, Sánchez-Doblado F, Sempau J, Seuntjens J, Siebers JV. Phase-space database for external beam radiotherapy. In: Summary report of a consultants' meeting. Vienna: International Atomic Energy Agency; 2006.

[6] <http://www.multidata-systems.com/website/waterphantom-dosimetry/index.html>.

[7] Salvat F, Fernández-Varea JM, Sempau J. PENELOPE – a code system for Monte Carlo simulation of electron and photon transport. Barcelona: Nuclear Energy Agency; 2006.

[8] Hedin E, Bäck A, Swanpalmer J and Chakarova R. Monte Carlo simulation of linear accelerator Varian Clinac iX. Excerpt of report MFT-Radfys 2010:01.

[9] Pönisch F, Titt U, Vassiliev ON, Kry SF, Mohan R. Properties of unflatted photon beams shaped by a multileaf collimator. Med Phys 2006;33(6):1738–46.

[10] Georg D, Kragl G, Wetterstedt Sa, McCavana P, McClean B, Knöös T. Photon beam quality variations of a flattening filter free linear accelerator. Med Phys 2010;37(1):49–53.

[11] Tsiamas P, Sajo E, Cifter F, Theodorou K, Kappas C, Makrigiorgos M, Marcus K, Zygmanski P. Beam quality and dose perturbation of 6 MV flattening-filter-free linac. Phys Med 2014;30(1):47–56.

[12] Javedan K, Feygelman V, Zhang RR, Moros EG, Correa CR, Trotti A, Li W, Zhang GG. Monte Carlo comparison of superficial dose between flattening filter free and flattened beams. Phys Med 2014;30(4):503–8.

[13] González W, García-Ferreira I-B, Anguiano M, Lallena AM. A general photon source model for clinical linac heads in photon mode. Radiat Phys Chem 2015;117:140–52.

[14] Fippel M. Fast Monte Carlo dose calculation for photon beams based on the VMC electron algorithm. Med Phys 1999;26(8):1466–75.

[15] Jarry G, Verhaegen F. Patient-specific dosimetry of conventional and intensity modulated radiation therapy using a novel full Monte Carlo phase space reconstruction method from electronic portal images. Phys Med Biol 2007;52(8):2277–99.

[16] Mackie TR, Scrimger JW, Battista JJ. A convolution method of calculating dose for 15 MV x ray. Med Phys 1985;12(2):188–96.

[17] Butson MJ, Mathur JN, Metcalfe PE. Skin dose from radiotherapy X-ray beams: the influence of energy. Australas Radiol 1997;41(2):148–50.

[18] Ding GX. Energy spectra, angular spread, fluence profiles and dose distributions of 6 and 18 MV photon beams: results of Monte Carlo simulations for a Varian 2100EX accelerator. Phys Med Biol 2002;47(7):1025–46.

[19] Edimo P, Clermont C, Kwato MG, Vynckier S. Evaluation of a commercial VMC++ Monte Carlo based treatment planning system for electron beams using EGSnrc/BEAMnrc simulations and measurements. Phys Med 2009;25(3):111–21.

[20] Chow JCL, Jiang R, Leung MKK. Dosimetry of oblique tangential photon beams calculated by superposition/convolution algorithms: a Monte Carlo evaluation. J Appl Clin Med Phys 2011;12(1):108–21.

[21] Edimo P, Kwato MG, Vynckier S. Validation of XiO Electron Monte Carlo-based calculations by measurements in a homogeneous phantom and by EGSnrc calculations in a heterogeneous phantom. Phys Med 2013;29(6):631–8.