Journal of Radiotherapy in Practice

Journal of Radiotherapy in Practice (2017)
16, 155–160 © Cambridge University Press 2017
doi:10.1017/S1460396917000012

Original Article

Effects of density from various hip prosthesis materials on 6 MV photon beam: a Monte Carlo study

M. Z. Abdul Aziz[1], F. N. Mohd Kamarulzaman[2], N. A. S. Mohd Termizi[2], N. Abdul Raof[1], A. A. Tajuddin[2]

[1]*Oncological and Radiological Science Cluster, Advanced Medical and Dental Institute, Universiti Sains Malaysia, Penang, Malaysia,* [2]*School of Physics, Universiti Sains Malaysia, Penang, Malaysia*

(Received 24 October 2016; revised 21 December 2016; accepted 21 December 2016; first published online 21 February 2017)

Abstract

In radiotherapy planning, computed tomography (CT) images are used to calculate the dose in the patient. However, a high density hip prosthesis can cause streaking artefacts in CT images, which make dose calculations for nearby organs inaccurate. This study aim to quantify the impact of a hip prosthesis on 6 MV photon beam dose distribution using the Monte Carlo (MC) simulation. To quantify the radiation dose at the hip prosthesis accurately, image processing techniques were used to generate CT images free from streak artefacts. MATLAB software was used to produce computer-generated phantoms consisting of bone, titanium, stainless steel and CoCrMo. Percentage depth dose (PDD) and beam profile were used to analyse the impact of the hip prosthesis on the dose distribution of the photon beam. PDD showed that the absorbed dose was reduced as the density of the material increased, and the dose was reduced by as much as 49% when the photon beam struck the highest density material (CoCrMo, 8·2 g/cm^3). However, dose was increased at the tissue-hip prosthesis interface (depths of 4 and 19 cm). As the depth increased, the absorbed dose decreased due to attenuation of photons by the tissue and the metal.

Keywords: computer-generated phantom; dose perturbation; hip prosthesis; Monte Carlo; streak artefacts

INTRODUCTION

In radiotherapy treatment planning, computed tomography (CT) images are used to calculate the dose distribution in the patient. In patients with a high electron density hip prosthesis, however, the prosthesis can cause streaking artefacts in the images, making dose calculations for nearby organs complicated and inaccurate. One solution to this problem is to avoid directing the photon beam towards the prosthesis, but this is not always feasible. When it is possible to avoid the hip prosthesis, doses reaching organs at risk, such as the rectum and the bladder, may be higher.[1]

To better understand the photon interaction with high-density metal, an accurate radiation interaction model is needed. In this model, the real tissue composition should be estimated instead of using water with different densities to mimic all tissue types.[2] Conventional radiation interaction models fail to eliminate the

Correspondence to: M. Z. Abdul Aziz, Oncological and Radiological Science Cluster, Advanced Medical and Dental Institute, Universiti Sains Malaysia, 13200 Kepala Batas, Penang, Malaysia. E-mail: mr.zahri@gmail.com

uncertainties originating from streak artefacts in CT images.[3,4] Streak artefact reduction techniques have been discussed comprehensively in the literature[3,5,6] by using the dual step adaptive thresholding technique, the sinogram correction method, and filtering methods to remove the artefacts from affected CT images.

Experimental methods using a dosimeter are the most accurate techniques for quantifying the radiation dose in the medium and for understanding the fundamental interactions between photons and the medium. Phantoms composed of different materials are commonly used in place of human tissues in radiation studies, but the dimensions of phantoms and dosimeter factors can affect the data. In addition, limited data make it difficult to establish accurate radiation interaction models. In situations in which experimental protocols are not feasible, Monte Carlo (MC) simulation, which is known for its dose calculation accuracy, can be used to develop an effective model. MC is one type of computational algorithm that is based on repeated random sampling to compute the results. MC dose simulation has been reported to provide low uncertainty calculation (<2%) in extreme inhomogeneities dose calculation.[7–9] In short, when the measurements of MC dose planning is carefully benchmarked, it can provide a valuable additional tool for treatment planning when difficult measurement situations occurr.[2]

In the present study, dosimetric calculation was performed to assess the effects of various hip prosthesis materials on 6 MV dose distributions using a MC source code (BEAMnrc and DOSXYZnrc). MC simulation was able to do a calculation in various materials and geometries without requiring extensive experimental measurements to be taken. The results of this study serve as a guideline for dose calculation whenever the primary beam must be directed at the hip prosthesis materials.

MATERIALS AND METHODS

Phantom scanning and image processing technique

A phantom containing Perspex and Teflon to represent soft tissue and the femoral head of the human hip, respectively, was prepared for use in this study (Figure 1a). The phantom (total size 14 × 28 × 22 cm) was scanned using a Toshiba CT simulator system (Toshiba Aquilion 64, Toshiba Medical Systems, Tokyo, Japan) to obtain the tomographic images (Figure 1b). The phantom was custom made based on Asian male pelvic size and consisted of Perspex (1·18 g/cm^3) to represent human tissue and Teflon (2·20 g/cm^3) to represent the head of the femur. To quantify the radiation dose at the hip prosthesis accurately, CT images should be free from the influences of metal streak artefacts. For this reason, image processing techniques were used to build computer-generated phantoms consisting of different prosthesis materials and densities substituting the Teflon femur head. CTCREATE software was used to convert the Teflon's density to that of various hip prosthesis materials using the data listed in Table 1.

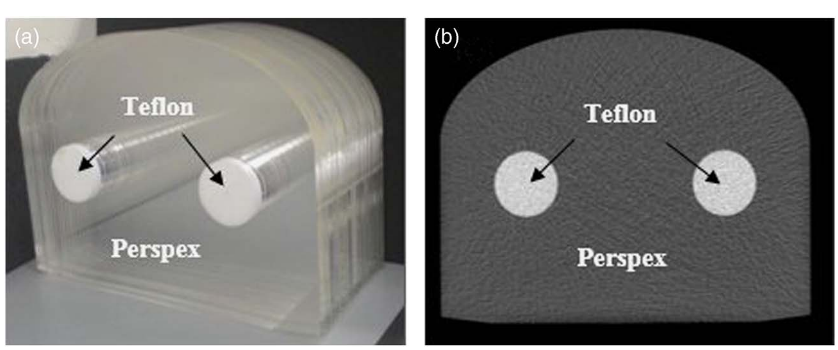

Figure 1. (a) A phantom made from Perspex and Teflon used in this study. (b) An image of the phantom scanned using a 64 multislice computed tomography simulator system.
Notes: Teflon can be observed clearly in the image.

https://doi.org/10.1017/S1460396917000012 Published online by Cambridge University Press

MC modelling, simulation and beam setup

The MC technique was used in this study to quantify the dose distribution in the Perspex/Teflon hip prosthesis and in the computer-generated phantoms. The MC model used in this study was obtained from the International Atomic Energy Agency (IAEA) MC database for the linear accelerator (Siemens Primus, Siemens Medical Systems, Concord, CA, USA), which contains validated accelerator beam data (phase-space file) from various model types, beam energies and field sizes. The phase-space data were executed in BEAMnrc code, and the output of BEAMnrc source code was used to calculate the dose distribution in the DOSXYZnrc source code. This study was performed using a 6 MV photon beam, $10 \times 10\ cm^2$ field size and 100 cm source to surface distance (SSD). The beam was directed lateral to the phantom as shown in Figure 2 to determine the maximum perturbation that usually occurs in the clinical setting. The number of histories used in DOSXYZnrc was 150 million (~1 hour calculation time). MC transport parameters (photon cut-off energy and electron cut-off energy)were set to 0·01 and 0·7 MeV, respectively.

Table 1. *Density and composition of materials used in the DOSXYZnrc simulation*

Materials	Density (g/cm^3)
Air	0·30[10]
Water	1·00[10]
Bone	2·08[10]
Titanium	4·48[11]
Stainless steel	6·45[12]
CoCrMo	8·20[12]

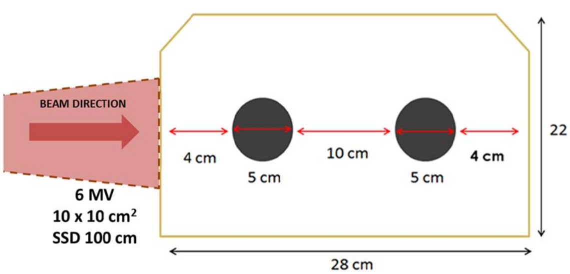

Figure 2. Photons with energy 6 MV were directed lateral to the phantom.
Notes: The first and second Teflon pieces are located 4 and 19 cm, respectively, from the surface.

RESULTS AND DISCUSSION

Siemens Primus model validation

The spectral distribution was plotted at the phantom surface with SSD 100 cm for the $10 \times 10\ cm^2$ field size (Figure 3). The average photon energy of the 6 MV photon beam was approximately one-third of the maximum nominal energy. The energy spectra of incident photon peaks were found at 0·5 MeV, which is similar to that previously reported by Aljamal and Zakaria.[8] The phase-space file downloaded from IAEA MC database was confirmed as 6 MV photon beam file due to the maximum photon energy observed as 6 MeV in the spectrum.

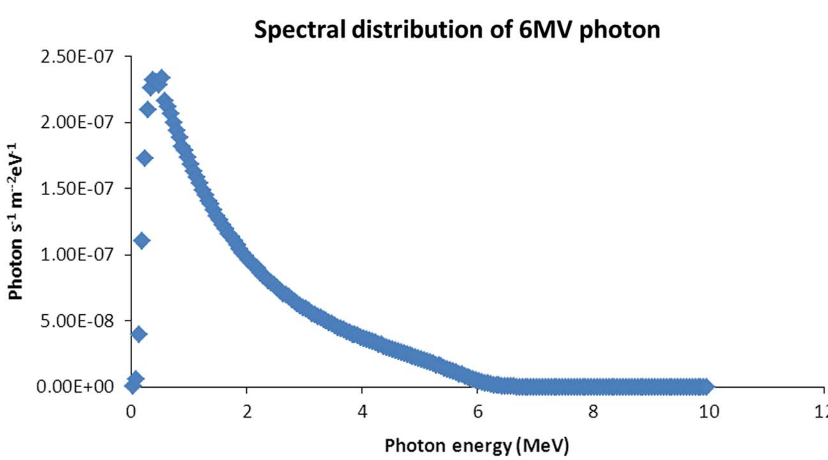

Figure 3. Spectrum of 6 MV photons from the International Atomic Energy Agency phase-space database (Siemens Primus).

https://doi.org/10.1017/S1460396917000012 Published online by Cambridge University Press

Scatter plot analysis also shows that the field size was $10 \times 10\,cm^2$ for both the X and Y axis (Figure 4).

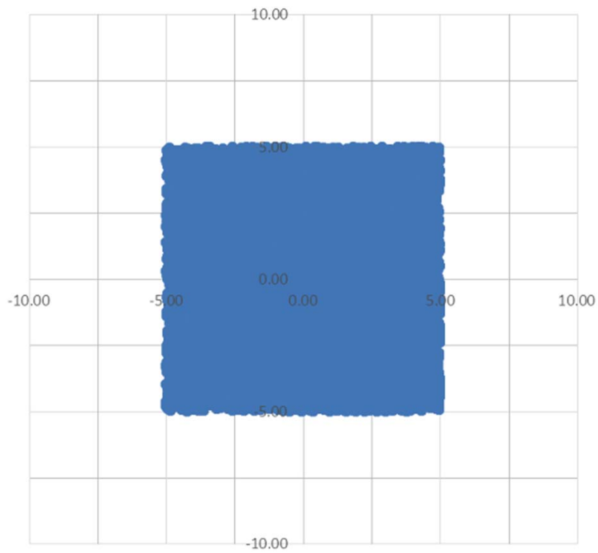

Figure 4. Scatter plot analysis illustrates a precise $10 \times 10\,cm^2$ field size of the simulated model.

MC dose calculation

The DOSXYZnrc was used to quantify the dose distribution of the 6 MV photon beam from the Siemens Primus linear accelerator. As a reference, the plot of percentage depth dose (PDD) of water (Figure 5) shows that the dose reached its d_{max} at 1·5 cm depth. After that, the dose decreased significantly until it reached the exit point of the phantom. PDD and beam data were used to analyse the impacts of the hip prosthesis on the dose distribution of the photon beam. PDD data showed that the absorbed dose decreased as the photon beam struck the higher density materials (bone, titanium, stainless steel and CoCrMo). The dose also increased minimally at both interfaces of Perspex high-density regions.

Further analysis showed that as the depth increased, the absorbed doses decreased by different magnitudes depending on the density of the material and the location. The dose was least perturbed at 0·5 cm depth and most perturbed at depth 9·5 cm from the surface. Thus, when a high-density prosthesis is located between

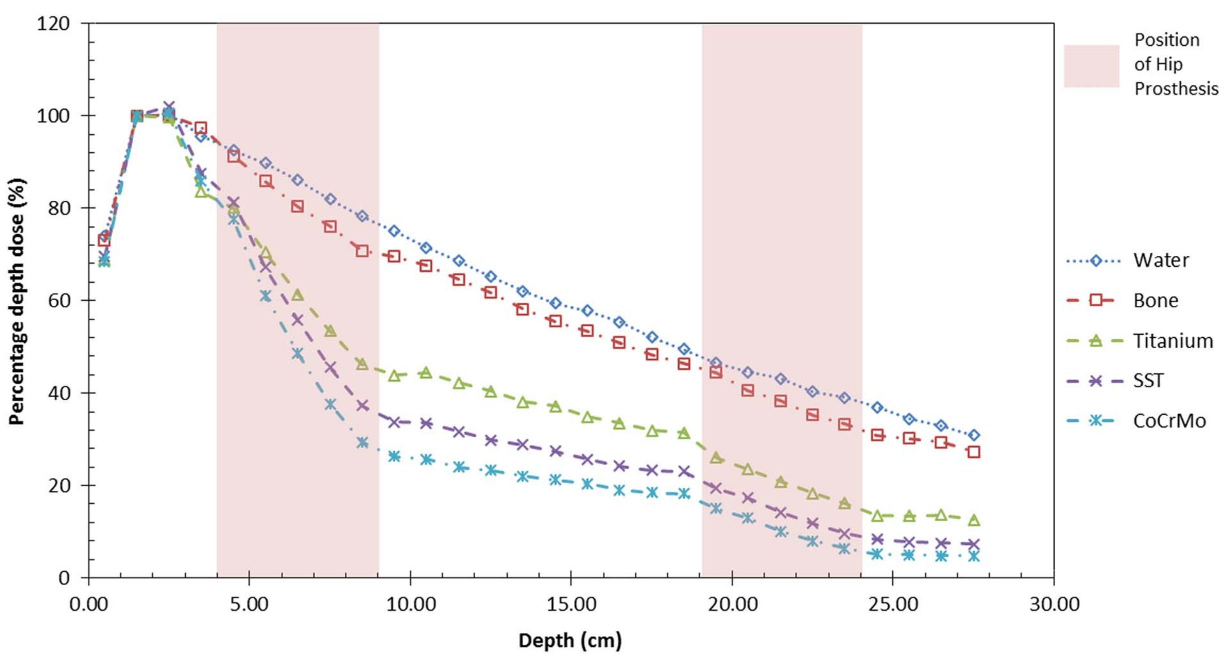

Figure 5. Percentage depth dose of the 6 MV photon beam oriented transverse to the various materials with different densities [water, bone, titanium (Ti), stainless steel (SST) and CoCrMo].
Notes: Drastic perturbation of doses were observed at depths of 4–9 cm (first femoral head position) and 19–24 cm (second femoral head position). Water ρ, $1\,g/cm^3$; bone ρ, $2{\cdot}08\,g/cm^3$; Ti ρ, $4{\cdot}48\,g/cm^3$; SST ρ, $6{\cdot}45\,g/cm^3$; and CoCrMo ρ, $8{\cdot}20\,g/cm^3$.

https://doi.org/10.1017/S1460396917000012 Published online by Cambridge University Press

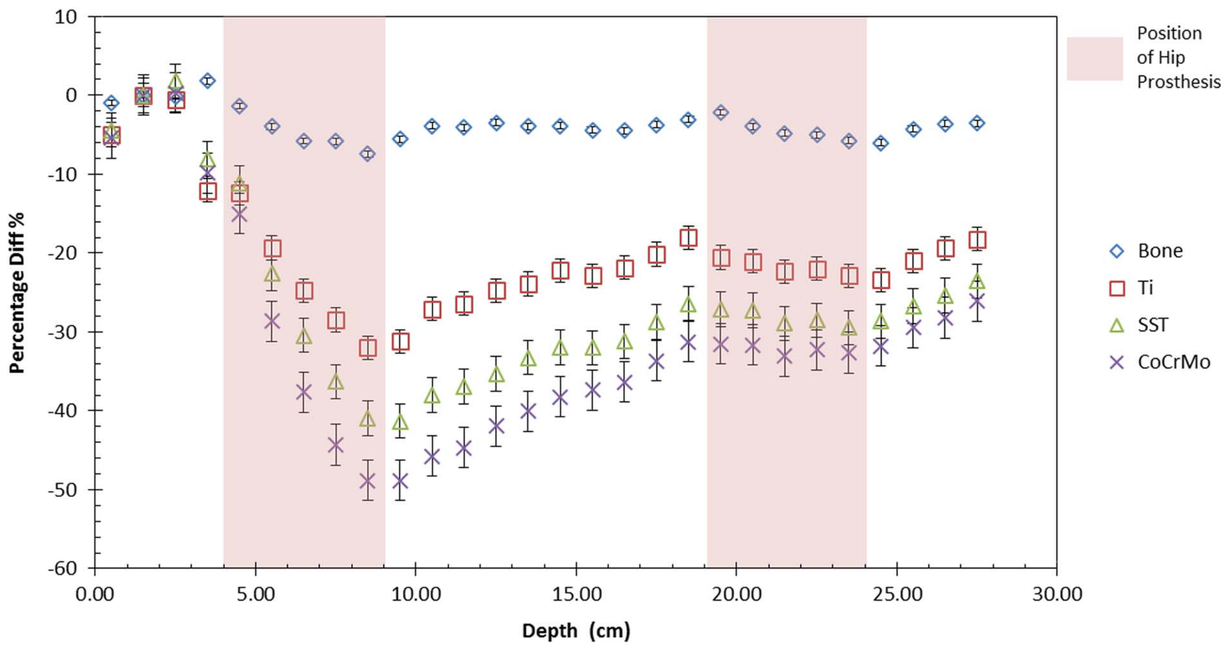

Figure 6. Percentage difference of dose perturbation of the 6 MV photon beam oriented transverse to various materials with different densities [water, bone, titanium (Ti), stainless steel (SST) and CoCrMo].
Notes: Bone, titanium and stainless steel effects on dose distribution were as high as 7, 32 and 41%, respectively, compared with water. The highest perturbation was observed for CoCrMo, for which a 49% difference was calculated.

beam and tumour, the beam weighting must be increased to deliver a sufficient dose to the tumour (i.e., the prostate) but at the same time the hot spot at the surface must be avoided. Of the high-density materials tested, the CoCrMo hip prosthesis material had the highest density, and it perturbed more radiation compared with bone, titanium and stainless steel. Figure 6 shows that the magnitude of dose perturbation was directly proportional to the density of the material struck by photons. Bone with density of 2·08 g/cm^3 was the least perturbed material followed by titanium (4·48 g/cm^3) and stainless steel (6·45 g/cm^3), with 32 and 41% dose difference relative to water, respectively. For CoCrMo, the dose difference was 49%. Overall, the contribution of backscatter to the PDD curve was minimal at the interfaces of the phantom (i.e., surrounding tissue).

CONCLUSIONS

The presence of a high-density hip prosthesis in a patient makes it difficult to calculate the dose distribution prescribed for the target and the surrounding tissues in treatment planning. The PDD and beam profile generated in this study for several types of hip prosthesis materials showed that high-density materials attenuated the photon beam to a significant extent relative to water. With an increase in the density of the material transversed by the 6 MV photon beam, attenuation of the beam increased and perturbation of the dose increased, resulting in a dose reduction as high as 49% for the densest (CoCrMo) material tested. The technique used in this study successfully quantified the perturbation effect on a dedicated pelvic phantom, whereas excluding the potential dose uncertainties arising from streak artefacts on CT images.

Acknowledgements

The authors would like to extend their gratitude to the Department of Higher Education (Malaysia) for providing a grant under Fundamental Research Grants Scheme (FRGS) 203/CIPPT/6711341. Appreciation also goes to the staff of the Radiotherapy Unit of the Advanced Medical and

Dental Institute at Universiti Sains (USM) the School of Physics at USM, Radiotherapy and Oncology Department at Universiti Sains Malaysia (USM) and the staff of the Radiology Department at Universiti Sains Malaysia (USM).

References

1. Palleri F, Baruffaldi F, Angelini A L, Ferri A, Spezi E. Monte Carlo characterization of materials for prosthetic implants and dosimetric validation of Pinnacle TPS. Nucl Instrum Methods Phys Res B 2008; 266: 5001–5006.
2. Reynaert N, Van de Marck S C, Schaart D R et al. Monte Carlo treatment planning for photon and electron beams. Radiat Phys Chem 2007; 76: 643–686.
3. Abdul Aziz M Z, Yusoff A L, Osman N D, Abdullah R, Rabaie N A, Salikin M S. Monte Carlo dose calculation in dental amalgam phantom. J Med Phys 2015; 40: 150–155.
4. Bazalova M, Beaulieu L, Palefsky S, Verhaegena F. Correction of CT artefacts and its influence on Monte Carlo dose calculations. Med Phys 2007; 34: 2119–2132.
5. Osman N D, Salikin M S, Saripan M I, Aziz M Z A, Daud N M. Metal artefact correction algorithm based-on DSAT technique for CT images. 2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES), 8–10 December 2014, Kuala Lumpur, pp. 324-327, 2014.
6. Abdoli M, Mohammad Reza A Y, Ahmadian A, Sahba N, Zaidi H. A novel approach for reducing dental filling artifact in CT-based attenuation correction of PET data. IFMBE Proc 2009; 22: 492–495.
7. Abdul Aziz M Z, Yusoff A L, Salikin M S. Monte Carlo electron beam dose distribution near high density inhomogeneities interfaces. World Acad Sci Eng Technol 2011; 58: 338–341.
8. Aljamal M, Zakaria A. Monte Carlo modelling of a Siemens Primus 6 MV photon beam linear accelerator. Aust J Basic Appl Sci 2013; 7 (10): 340–346.
9. Toossi M T B, Ghorbani M, Akbari F, Sabet L S, Mehrpouyan M. Monte Carlo simulation of electron modes of a Siemens Primus linac (8, 12 and 14 MeV). J Radiother Pract 2013; 12: 352–359.
10. International Commission on Radiation Units and Measurements. Photon, Electron, Proton and Neutron Interaction Data for Body Tissues (Report 46). Washington, DC: ICRU, 1992.
11. Wieslander E, Knoos T. Dose perturbation in the presence of metallic implants: treatment planning system versus Monte Carlo simulations. Phys Med Biol 2003; 48: 3295–3305.
12. Bazalova M, Coolens C, Cury F, Childs P, Beaulieu L, Verhaegen F. Monte Carlo dose calculation for phantoms with hip prosthesis. J Phys Conf Ser 2008; 102: 1–8.