Dosimetric effects of a high-density spinal implant

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Abstract. In this study, a treatment plan for a spinal lesion, with all beams transmitted though a titanium vertebral reconstruction implant, was used to investigate the potential effect of a high-density implant on a three-dimensional dose distribution for a radiotherapy treatment. The BEAMnrc/DOSXYZnrc and MCDTK Monte Carlo codes were used to simulate the treatment using both a simplified, rectilinear model and a detailed model incorporating the full complexity of the patient anatomy and treatment plan. The resulting Monte Carlo dose distributions showed that the commercial treatment planning system failed to accurately predict both the depletion of dose downstream of the implant and the increase in scattered dose adjacent to the implant. Overall, the dosimetric effect of the implant was underestimated by the commercial treatment planning system and overestimated by the simplified Monte Carlo model. The value of performing detailed Monte Carlo calculations, using the full patient and treatment geometry, was demonstrated.

1. Introduction
High-density, metallic implants are often necessary to for the survival or quality of life of radiotherapy patients. However, these implants can cause problems for successful radiotherapy treatment planning, when they are located within or close to targeted lesions and organs. In addition to producing star and shadow artefacts in CT images, the presence of high-density and high-atomic-number implants can also result in inaccurate density assignment and underestimation of dosimetric effects, by conventional treatment planning systems.

Monte Carlo simulations have been shown to provide valuable reference data, for establishing the accuracy of treatment planning dose calculation algorithms, in the presence of heterogeneous tissue [1]. Previous Monte Carlo simulation studies of the dosimetric effects of high-density implants have relied on the use of simplified anatomical models (usually homogeneous water) and simplified implant models (usually cylinders, cubes or planes) [2, 3]. It has been argued, however, that the results of simple phantom studies may exaggerate the effects of density heterogeneities on dose, since patient treatments use complex treatment plans, with multiple gantry angles, delivered to complex anatomies where variable thicknesses of air and bone intersect the radiation beams [4].

The current study examines one clinical case, where a radiotherapy treatment was planned for delivery through a titanium vertebral implant, and evaluates the reliability of a simplified Monte Carlo
model of this complex treatment, in comparison with a Monte Carlo simulation that includes the full complexity of the patient anatomy and treatment geometry.

2. Methods

2.1. Treatment plan
A sample treatment plan was devised using CT data and prescription information from a recent patient treatment. The treatment involved the surgical excision of the laminae from seven vertebrae in the cervical-thoracic vertebrae [5], and the implantation of a Vertex Max reconstruction system (Medtronic, Sydney, Australia). This titanium implant consisted of two rods which were attached, via two parallel rows of screws, to the affected vertebrae.

The radiotherapy treatment was planned using the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, USA), version 8.6, and dose was calculated using the AAA convolution-superposition algorithm. In order to provide an apparently homogeneous dose to the targeted tumour, the sample treatment plan used in this study used a forward-planned (field-in-field) IMRT technique. All beams were transmitted through the implant before reaching the targeted lesion. The titanium implant was expected to have a substantial effect on the dose to the targeted region of the spinal cord.

2.2. Monte Carlo simulations
The treatment was planned for delivery using a 10 MV photon beam from a Varian iX linear accelerator (Varian Medical Systems, Palo Alto, USA) with a Millennium 120-leaf MLC. A Monte Carlo linear accelerator model with output matched to the clinical beam was designed and commissioned to match clinical beam data, using BEAMnrc [6].

Using the DOSXYnrc Monte Carlo user code, rectilinear phantom model was designed to approximate the major features of the implant in the patient’s neck. Fourteen $1 \times 1 \times 0.8 \text{ cm}^3$ blocks of titanium, with density 4.54 g/cm$^3$ were positioned in two parallel rows at 2 cm depth in a $10 \times 10 \times 29 \text{ cm}^3$ volume of water, representing the titanium screw heads that comprised the most substantial parts of the implant. In each row, adjacent titanium blocks are separated by 0.6 cm or 1.0 cm, mimicking the pattern of screw positions in the patient’s implant.

The simple, rectilinear model included neither the remaining components of the implant (narrow screw shafts, rods joining the screws and base plate fixing the implant to the skull), nor the air in the trachea, nor the bones of the spine, shoulders or skull. Additionally, only one $19.3 \times 3.0 \text{ cm}^2$ rectangular 10 MV photon field from the planned treatment was applied to the simplified model.

In order to produce a more-detailed Monte Carlo simulation, including the full complexity of the treatment to the patient’s heterogeneous anatomy, treatment planning data including the CT images, treatment plan, structures (including the contours of low-density shadow artefacts produced by the high-density implant) and dose distribution were exported from the treatment planning system in DICOMRT format and used as inputs for MCDTK (the Monte Carlo DICOM ToolKit) [7, 8], which produced BEAMnrc and DOSXYnrc input files based on treatment plan information, and which produced a voxelised DOSXYnrc ‘egsphant’ phantom model from the CT data. To produce an egphant file that was not affected by CT scanning artefacts, the MCDTK code was adapted to reassign the materials and densities of the voxels enclosed by the artefact contours exported from the treatment planning system, so that they matched the surrounding tissues.

A Monte Carlo simulation of the complete radiotherapy treatment was completed, and MCDTK was used to convert the resulting Monte Carlo simulation output into a three dimensional array of absolute dose values, taking into account the number of monitor units per beam as well as the effect of backscatter from the secondary collimators into the linear accelerator’s monitor chamber [9, 10].
3. Results and discussion

Figures 1(a), (b) and (c) show the results of evaluating dose in the simple, rectilinear phantom, using the treatment planning system and the Monte Carlo calculations. In figure 1(b), profiles through the implant indicate that the treatment planning system’s calculation predicted an increase in absorbed dose within the implant components, which had an apparently minimal effect on the dose between the implant components. By contrast, the Monte Carlo dose distribution shows a decrease in dose within the implant components, and a dramatic increase in scattered dose adjacent to implant components, which is compounded for the section where the model screw heads are placed closer together. Additionally, the Monte Carlo data show that the attenuation of the beam by the implant results in an obvious depletion of dose 5 cm downstream, while the treatment planning system’s calculations suggest that the implant has a reduced effect at this distance. In the dose shadow of the implant components, the treatment planning system and Monte Carlo calculations differ by up to 9.5%. This is similar to results obtained in previous simple-phantom studies where Monte Carlo calculations were compared with treatment planning dose predictions generated using CADPLAN [2] and Pinnacle [3].

Figure 2 shows the results of dose calculations made for the full patient treatment, using the conventional treatment planning system and Monte Carlo, and provides immediate visual confirmation of the effects predicted by the simplified model simulation: isodoses obtained from the Monte Carlo data describe regions of high dose between the implant screws as well as regions of depleted dose on the anterior (downstream) side of the implant, while these features are barely evident in the isodoses obtained from the treatment planning system’s dose calculation.

There are differences between the results of the detailed patient treatment simulation and the results obtained using the simplified model. The rectilinear model predicts regions of under-dosage of up to 9.5% at a depth 5 cm downstream of the implant, while the patient treatment simulation shows regions of up to 5% under-dosage, at depths 2-3 cm downstream of the implant. This difference in the level of under-dosage seems to result from the use of multiple fields delivered from three gantry angles, in the clinical treatment plan, so that regions under-dosed by one beam are compensated by another. The regions of 5% under-dose remain concerning, however, since they are located within the planned treatment volume (PTV). The variation in dose across the PTV is predicted by the planning system as 10%, but the detailed Monte Carlo model shows that this value increases to 16%, when the dosimetric effects of the implant are accurately evaluated.

Figure 1: Results for rectilinear phantom: (a) Dose image from Monte Carlo simulation (lighter pixels indicate higher dose, darker pixels indicate lower dose), showing the locations of the profiles shown in (b), as a vertical white line, and (c), as a horizontal white line. Profiles in (b) and (c) are from the treatment planning system’s dose calculation (grey lines) and from Monte Carlo simulations (black lines). In profiles (b) and (c), the upper pair of curves represent dose calculated at the depth of the implant and the lower pair of curves represent dose calculated at a depth 5 cm downstream of the implant.
4. Conclusion

The Monte Carlo simulations done using both a simplified and detailed model of a radiotherapy treatment planned for a patient with a high-density implant showed that the implant had a profound effect on local and downstream dose, and that this effect was substantially underestimated by the treatment planning system. The simplified model of the patient geometry, irradiated by one radiotherapy beam, provided useful qualitative information. However, the use of this simple model, alone, might lead to an overestimation of the dosimetric effect of the implant on the whole patient treatment. The detailed Monte Carlo simulation of the entire treatment provided information in regions of specific clinical interest, such as the heterogeneity of dose to the PTV, which was not accurately predicted by the planning system and could not be obtained from the simplified Monte Carlo model.

This study confirms the value of performing additional Monte Carlo calculations, preferably using detailed patient models, in cases where treating through high-density implants cannot be avoided.

5. Acknowledgments

This study was supported by the Australian Research Council, the Wesley Research Institute, Premion and the QUT, through linkage grant number LP110100401. Computational resources used in this work were provided by the HPC and Research Support Unit, QUT.

6. References

[1] Papanikolaou N and Stathakis A 2009 Med. Phys. 36 4765-75
[2] Ding G X and Yu C W 2001 Int. J. Radiat. Oncol. Biol. Phys. 51 1167-75
[3] Palleri F et al 2008 Nucl. Instrum. Methods Phys. Res. B 266 5001-6
[4] Seco J and Evans PM 2006 Med. Phys. 33 540–552
[5] Sinha A K et al 1997 Can. J. Surg. 40 218-26
[6] Rogers D W O et al 1995 Med. Phys. 22 503-24
[7] Crowe S B et al 2012 IFMBE Proc. 39 1803-6
[8] Crowe S B et al 2012 IFMBE Proc. 39 1807-10
[9] Popescu I A et al 2005 Phys. Med. Biol. 50 3375-92
[10] Kairn T et al 2009 Australas. Phys. Eng. Sci. Med. 32 129-35