Characterization of materials for prosthetic implants using the BEAMnrc Monte Carlo code

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Abstract. Metallic implants degrade image quality and perturb severely the patient dose distribution in external beam radiotherapy. Furthermore, conventional treatment planning systems (TPS) do not accurately account for tissue heterogeneities, especially at the interfaces where high Z gradients are present. This work deals with the accurate and systematic characterization of materials used for prosthetic implants. The dose calculation engine used in this investigation is the BEAMnrc Monte Carlo code. A detailed comparison versus experimental data was carried out for two clinical photon beam energies (6MV and 18MV). Our results show that in both cases a very good agreement (within ± 2%) between calculations and experiments was achieved.

1. Introduction
Radiotherapy planning for patients with prosthetic implants is challenging because metallic hip prostheses influence heavily the dose distribution prescribed to the target and to the surrounding tissues. The dosimetric aspects of external beam treatment of patients with pelvic malignancies with high atomic number hip prostheses have been reviewed and special beam arrangements, in most cases avoiding the direct irradiation of the prosthesis, have been advised (Reft et al 2003 and references therein). The detailed knowledge of the dose perturbation caused by the presence of high density prosthetic implants is an important treatment planning resource for the determination of the correct dose distribution delivered to patients undergoing external beam radiotherapy (Keall et al 2003). Recently Buffard et al (2005) compared Monte Carlo calculation with measurements for a titanium alloy femoral stem irradiated with $^{60}$Co source. In this work we evaluated the dosimetric characteristics of some of the most common materials used for prosthetic implants, providing a systematic validation of our MCTP models vs. experimental data for clinical 6MV and 18MV photon beams.

2. Materials and Methods
In this investigation we carried out a MC model characterization for the following materials: titanium alloy, stainless steel alloy, CoCr alloy and ultra high molecular weight polyethylene (UHMWPE). Following the regional register of orthopaedic prosthetic implants (http://ripo.cineca.it) these materials were used to manufacture ≈ 50% of acetabular cups.

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and stems between 2000 and 2004. For our experiments the materials were produced in cylinders of 15 cm length and 3 cm diameter. The full list of implant materials used in this work is given in Table 1.

Two experimental configurations were used: (a) cylinders were immersed in a water phantom and dose profiles at different depths were acquired with a semiflex ion chamber (type 31010, PTW, Freiburg, Germany); (b) cylinders were inserted in a specially built PMMA slab (4 cm thickness) to be used in conjunction with a RW3 polystyrene phantom (PTW, Freiburg, Germany). In this case planar dose maps were conveniently acquired with a 2D array of ion chambers (Spezi et al 2005). This configuration also allowed the point of measurements to be closer to the cylinder surface (2.4cm from the cylinder central axis vs 3.5cm in the case of ion chamber measurements in water tank). In both experiments, shown in Figure 1 and Figure 2 respectively, the SAD was set to 100 cm and the SSD to 95 cm. Clinical (10×10) cm² 6MV and 18MV photon beams were provided by a Siemens Oncor IMRT Impression + and incorporating an Optifocus 82 leaves MLC. An accurate MC model for both energies of the linac was commissioned for field sizes ranging from (0.2×0.2) cm² to (25×25) cm². The MC code used in this investigation was BEAMnrc (Rogers et al 1995). Material composition and densities required for the MC modelling were provided by the manufacturers.

Table 1. Implant materials and corresponding physical density.

| Material       | Trade Name | Standard  | Density (g/cm³) |
|----------------|------------|-----------|-----------------|
| Titanium alloy | Ti6Al4V    | ISO 5832/3 | 4.30            |
|                | Ti6Al4Nb   | ISO 5832/11 | 4.52           |
| Co-Cr alloy    | Vitallium  | ISO 5832/12 | 8.30            |
| Steel          | Orthinox   | ISO 5832/9  | 8.00            |
|                | Stainless steel | ISO 5832/1 | 8.00            |
| Polyethylene   | UHMWPE     | ISO 5834/2  | 0.95            |

Figure 1. Experimental set-up for ion chamber measurements in water.  
Figure 2. Experimental set-up for measurements in solid water phantom.
3. Results
Our results show a good agreement between experimental data and MC calculations. A comparison of measurements (ion chamber) and MC profiles for the 18MV beam is depicted in Figure 3. Profiles were taken 8.5 cm below the water surface (i.e. 3.5 cm below the isocentre and central axis of the cylinder). This limit was determined by the presence of the arm, and associated gears, to which the ion chamber was attached inside the water tank. Both ion chamber signal and MC calculations were independently normalized to the value recorded/calculated at \( d_{\text{max}} \) for the open field (Figure 3a). Since the results for titanium alloys are very similar only the type of alloy with higher density (Ti6Al7Nb) is shown. Figure 4 shows a comparison between experiments (2D ARRA Y) and MC for the 6MV photon beam. Profiles were taken 2.4 cm below the isocentre. Independent normalization to the central axis dose was carried out for the irradiation of a homogeneous RW3 polystyrene phantom (Figure 4a). As shown, the calculated profiles fit well (within ± 2% global difference) the dosimetric dataset for all the considered materials and for both beam energies.

4. Conclusions
The validation of the dosimetric properties of materials used in MCTP is a fundamental condition for the accurate calculation of clinical dose distributions. In this investigation we characterized six materials for MCTP simulation of pelvic irradiation of patients with hip prostheses. The method set-up in this work could be successfully extended to other clinical sites and used in the clinical practice when the information regarding the type of implanted material is available.

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Figure 4. Profile comparison for measurements and MC simulation of the 6 MV photon beam (cf. Figure 2).

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