Simulation of Scattering Effects of Irradiation on Surroundings Using the Example of Titanium Dental Implants: A Monte Carlo Approach

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Abstract. Occasionally, head and neck cancer patients treated with high-energy X-rays and gamma rays have titanium dental implants. The aim of this study was to calculate alterations in the irradiated bone caused by a foreign body, representing a titanium implant in size and physical qualities, using a stochastic (Monte Carlo) simulation. A clinical linear accelerator was simulated using BEAM/EGS4. The calculations showed that the presence of an implant results in differences of the dose distribution all around the implant. Titanium dental implants in the field of irradiation were capable of causing significant radiation scattering. The risk for dose enhancement was notably important for the bone in direct contact with the foreign body. Therapists involved in radiation planning should consider the impact of dental implants on the radiation beam as a putative cause of osteoradionecrosis.

Irradiation of the head and neck region as an adjunct to ablative surgery or applied with curative intention is one of the most important therapies for head and neck cancer (1-3). Due to the rapidly increasing improvements of rehabilitative oral medicine, namely, restorative and implant dentistry, intentionally placed metallic foreign bodies may lie in the irradiation field and cause concern for radiotherapy planning (4, 5). Indeed, there is no general agreement on explantation or preservation of metal dental implants in patients subjected to irradiation therapy (6-8). Some authors argue that metallic foreign bodies in irradiated individuals do not alter the tissue-adjusted irradiation by any measurable manner (5, 8). Others stress the impact of implants on the route of the central beam of the irradiation source (4, 9). They point to a quantitatively noteworthy deviation of X-rays following the collision of irradiation and implants, resulting in scattering radiation effects on tissues beyond the threshold of biological compensation (4, 9). Clinical studies usually address the risk of implant failures in irradiated jaws (8) and human studies on dental implants exposed to therapeutic irradiation are casuistic (5). This study calculated alterations to the irradiation of bone caused by a foreign body, representing in size and physical qualities a titanium implant, using a stochastic (Monte Carlo) simulation (10).

Materials and Methods

Monte Carlo simulation. A two-step Monte Carlo simulation was used. First, a clinical linear accelerator was simulated using BEAM/EGS4. BEAM is an EGS4-based code for modelling beams on a component-by-component basis and for predicting beam characteristics from clinical linear accelerators (11). The generic accelerator consists of a number of predefined components that enable the simulation of most available linear accelerators. Materials and dimensions must be defined in associated files. The components were applied to model the target, primary collimator, flattening filter, monitor chamber and jaws. The vendor-specific data were obtained from R. Siochi (12). A 2×2 cm² 6 MV photon beam of a Siemens Mevatron was modelled at a distance of 100 cm from the target. Initially 10⁹ electrons with energy of 5.58 MeV impinged on the target. No variance reduction techniques were used. The output of this simulation was a phase-space file which contained all the necessary information about each particle crossing a plane, i.e. charge, energy, position in terms of x, y, and z coordinates, impulse (direction), and z-position of the last interaction. This information was used as input for the second part of the simulation. Irradiating a water phantom containing an implant made of titanium, the dose distribution in the phantom was investigated. This simulation was performed using the EGS4 user code DOSXYZ (13). The implant (density: 4.49 g/cm³, dimensions: 10×10×10 cm³) was positioned at a depth of 3 cm in the water tank (Figure 1), with its axis parallel to the surface. It was modelled using 84 voxels (each 0.1×0.2×0.1 cm³), resulting in a diameter of 0.4 cm and a total length of 1.6 cm. The results of the simulation were compared with the results of a simulation of a plain water tank (same dimensions).
Results

The results of the Monte Carlo simulations are shown in Figures 1-3. Figure 1 shows the simulated dose distribution in the water phantom. The position of the implant leads to a dose reduction directly behind it (Figure 2). To obtain more information about the influence of the implant on dose distribution, Figure 2 shows simulated depth-dose curves (central beam) for the cases with and without the implant. The position of the implant is shown by the two dashed lines. Directly behind the implant, the dose is reduced by almost 16%. This is a result of absorption in the titanium. With growing depth, the difference decreases due to scattering. Photons outside the irradiation field are scattered in the region behind the implant. This compensates for some of the absorption, so that the difference stabilises at 5%, compared with the depth-dose curve for the plain water phantom. Directly in front of the implant, the dose increases. For the implant, the dose is almost 10% higher than the dose in the plain phantom and due to differences in the density of the two materials. The density of the titanium is 4.49 times higher than the density of the surrounding water, resulting in backscattering of photons and electrons and production of secondary electrons on the implant surface. Figure 3 shows cross-plane profiles in a depth of 3 cm for both situations. Due to the fact that the implant is localised at a depth of 3 cm, the figure shows a cross-section of the implant. The presence of the implant also results in differences of dose distribution immediately next to the implant, not only behind and in front of it. Compared to the dose in the plain water phantom, the dose immediately next to the implant is almost 8% higher. Again, this is a result of scattering effects of the photons and electrons.

Discussion

Occasionally head and neck cancer patients treated with high-energy X-rays and gamma rays have titanium dental implants in their maxillae or mandibles. The resulting effect of the bone-metal interface on the radiation dose is of interest for therapists and patients (1-9). This simulation of an irradiated mandible supported by a dental implant revealed measurable scattering radiation effects around the foreign body. Radiotherapy planning has to consider metallic implants in the irradiation field as a source of significant radiation scattering affecting adjacent soft tissues and bones. This effect may contribute to pathological processes in the bone and adjacent tissues, resulting in osteoradionecrosis (1-9).

The results of this simulation are in accordance with calculations of Mian et al. (14) who revealed that for $^{60}\text{Co}$, a 15% increase in dose was delivered to solid bone at the entrance side of the titanium. The increase in dose was nearly the same or slightly lower than for higher energy X-rays. In their irradiation model ionisation measurements for $^{60}\text{Co}$ gamma rays and 6 MV and 25 MV X-rays were used. They used a thin-window parallel-plate chamber to determine the magnitude of the dose enhancement caused by the backscattered electrons from titanium. The experimental results were substantiated by Monte Carlo simulations. Interestingly, the increase in dose fell off rapidly and became negligible at a distance of 1-2 mm from the interface. The authors concluded that backscattered dose should be taken into account when planning radiation therapy treatment for patients with dental implants.

On the other hand, Laass et al. (15) investigated two implant materials, titanium and tantalum, for their electron emission in response to therapeutic tumour irradiation. Both materials were compared, in their capacity as a source of irradiation scattering, to a substance equivalent to bone. The authors revealed a reaction of titanium similar to that of bone. On the contrary, a substantial increase in radiation was caused by tantalum which, consequently, should be removed from the radiation field.

A further study on this subject was performed by Wang et al. (16). They inserted 0, 1, 2, and 3 mm-thick bone substitute disks between the implant material and an ionisation chamber and they measured relative ionisation charges at implant/bone interfaces at the above mentioned distances away from the implant material. They used three implant materials: pure titanium, Ti-6Al-4V alloy, and a high gold content implant material. Irradiation was with high-energy 6 MV and 10 MV X-rays. Backscattered electrons decreased as the thickness of the bone substitute, and thus the distance between the implant material and the ionisation chamber, increased. This result was in accordance with the findings of Mian et al. (14). The results indicated that the highest dose enhancement occurred at a distance of 0 mm from the implant/bone interface for all the materials studied. Interestingly, the gold-alloy implant material had more average relative dose than pure titanium or Ti-6Al-4V alloy. In a further study, Wang et al. (17) modified their irradiation model and investigated the relative doses in buccal, lingual, mesial, and distal directions in proximity to the implant. They found no significant dependence of dose enhancement on bone topography. Again, bone in direct contact to the implant was at highest risk for irradiation dose enhancement.

Ozen et al. (18) and Beyzadeoglu et al. (19) investigated the impact of beam angle on scattering irradiation. The dose enhancement at different beam angles was less pronounced in 25 MV x-rays and more pronounced in $^{60}\text{Co}$ gamma irradiation. They concluded that for the radiation beams studied, the irradiation angle between scattering titanium dental implants and the central axis did not affect the total dose sufficiently to lead to osteoradionecrosis of the mandible.
Nicopoulou-Karayianni et al. (20) used a Monte Carlo approach to study the effect of diagnostic radiology in the course of implant dentistry. Given the hypothesis of about 6 radiographs per patient over a 6-month period for the planning, treatment and follow-up check of implantation, the maximum radiation dose at the cortical bone-titanium interface was estimated to be less than 20 mGy. These calculations were used for optimising dose reduction of digital radiography for implant dentistry (21).

The impact of metallic implants on the irradiation field in adjacent structures is still debatable. Binger et al. (22) revealed dose inhomogeneities of different dental implants during irradiation with high energy photons. These investigators used a phantom and ultra-thin thermoluminescent dosimeters. Measurements were performed at the interface of bone to soft tissue. They revealed a decrease of the dose immediately behind the implant with an increase of the implant thickness. In front of the implants, increases of the dosage were measured (18.2% in bone and 30.4% in soft tissues). This effect of a backscattering irradiation was not influenced by conditioning of the implant surfaces. On the other hand, a scattering irradiation effect was not measured when implants made of aluminium oxide ceramics were used.

Dental implants made of titanium in the irradiation field are capable of causing significant irradiation scattering. The risk for dose enhancement is notably important in the bone in direct contact with the foreign body. Therapists involved in irradiation planning are advised to consider the impact of dental implants on the irradiation beam as a putative cause of osteoradionecrosis.

References


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