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Effect of titanium dental implants on proton therapy delivered for head tumors: experimental validation using an anthropomorphic head phantom

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ABSTRACT: A dosimetric experiment was performed at the Medico-Technical Complex in the Joint Institute for Nuclear Research, Dubna, to investigate the effects of metallic dental implants in the treatment of head and neck tumours with proton therapy. The goal of the study was to evaluate the 2D dose distributions of different clinical treatment plans measured in an anthropomorphic phantom, and compare them to predictions from a treatment planning system. The anthropomorphic phantom was sliced into horizontal segments. Two grade 4 Titanium implants were inserted between 2 slices, corresponding to a maxillary area. GafChromic EBT2 films were placed between the segments containing the implants to measure the 2D delivered dose. Two different targets were designed: the first target includes the dental implants in the isocentre, and in the second target, the proton beam is delivered through the implants, which are located at the entrance region of the Bragg curve. The experimental results were compared to the treatment plans made using our custom 3D Treatment Planning System, named RayTreat. To quantitatively determine differences in the isodose distributions (measured and calculated), the gamma index (3 mm, 3%) was calculated for

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each target for the matrix value in the region of high isodose ($> 90\%$): for the experimental setup, which includes the implants in the SOBP region, the result obtained was 84.3%. When the implants were localised in the entrance region of the Bragg curve, the result obtained was 86.4%. In conclusion, the uncertainties introduced by the clinically planned dose distribution are beyond reasonable limits. The linear energy transfer spectra in close proximity to the implants were investigated using solid state nuclear track detectors (TED). Scattered particles outside the target were detected.

KEYWORDS: Dosimetry concepts and apparatus; Instrumentation for hadron therapy; Microdosimetry and nanodosimetry; Particle tracking detectors (Solid-state detectors)

Contents

1	Introduction	1
2	Materials and Methods	1
2.1	RayTreat (a non commercial TPS)	1
2.2	Proton-beam line	2
2.3	Film dosimetry (EBT2) and solid state nuclear track etched detectors (TED)	2
3	Results and Discussion	3
4	Conclusion	6

1 Introduction

Proton beam therapy is a radiation technique utilised to treat cancer diseases. It has been shown to involve lower entrance doses and improve preservation of healthy tissue, when compared to radiation therapies using photons. In our facility at the Medico-Technical Complex in the Joint Institute for Nuclear Research (JINR, Dubna, Russia), we specialise in treating complex cases of Head and Neck tumours. In the case of 3D conformal proton radiotherapy, the diagnosis procedure and treatment plan includes the immobilisation of the region to be irradiated; diagnosis and topometric imaging of the target (X Ray computed tomography (CT) and Magnetic Resonance Imaging); image analysis, using the Three-Dimensional Treatment Planning System; and the manufacture of individual collimators and boluses [1]. An accurate treatment is based on correct CT values (Hounsfield Units, HU), which are then calibrated to relative proton stopping powers. For a CT of a metallic material, the metallic artefacts corrupt the data. This can potentially affect the treatment outcome and introduce considerable errors in the calculated dose distribution [2–4] due to an incorrect calculated CT number near the dental implants.

The objective of this study was to evaluate the effect of dose perturbation caused by high-Z dental implants. Specifically, we performed the experiments using a proton beam to measure the 2D dose distribution and to study the Linear Energy Transfer Spectra (LET) in close proximity to the titanium implants. The literature contains few publications where the dose distribution has been investigated in the presence of metallic implants, either through simulations or experimentally, through simple geometric phantoms: [5–7].

2 Materials and Methods

2.1 RayTreat (a non commercial TPS)

To evaluate the accuracy of the pencil-beam algorithm of our custom 3D treatment planning software (TPS), named RayTreat, we made a comparison between the calculated and the measured 2D dose

distribution in an anthropomorphic head phantom (from Alderson®, Radiology Support Devices, Long Beach, CA, U.S.A.).

2.2 Proton-beam line

A horizontal fixed beam with a nominal energy of 173 MeV and field size of 10 cm × 10 cm was used. In the maxillary area (premolar tooth and molar tooth) we implanted two dental implants, manufactured from grade 4 titanium [8], with a density of 4.51 g/cm³ and an associated HU of 4095. It should be noted that the density and the CT number of titanium are much higher than are those of either normal tissue or dense bones and higher than the maximum values supported by CT scanners.

Two treatment plans have been created to study the following cases: 1st — the influence of dental implants in the Bragg peak region (angle of irradiation 90°, dose 2.5 Gy at isocentre) and 2nd — the influence of titanium implants at the entrance region of the Bragg curve (angle of irradiation 0°, dose 2.5 Gy). A range shifter was used to spread-out the Bragg peak (SOBP), and individual boluses and collimators were created for each target.

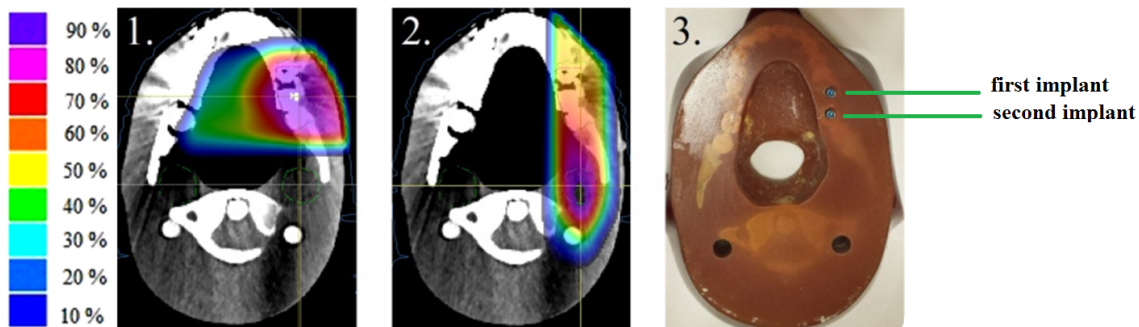


Figure 1. CT images with calculated 2D colour maps of a target that contains 2 implants: (1) in the plateau of the spread-out Bragg peak; (2) the second target is a deep localised tumour where the implants are localised at the entrance region; and (3) an image of the Alderson head phantom with dental implants insertions.

2.3 Film dosimetry (EBT2) and solid state nuclear track etched detectors (TED)

The dose distribution of the therapeutic proton beam in the presence of titanium implants was studied using GAFCHROMIC® EBT2 film (Ashland Inc., New York, U.S.A.). The LET spectra were detected using solid state nuclear track etched detectors (TED), namely HARZLAS TD-1 detectors (Nagase Landauer Ltd., Japan).

EBT2 Films. The phantom used in these experiments is constructed of slices. Radiochromic films cut in the shape of phantom's slice were placed between the 2 slices containing the dental implants. The films were calibrated for a dose range from 0 Gy to 3 Gy. The readout of the EBT films was delayed at least 24 hours after the irradiation to minimise the effects of post-irradiation colouration. The EBT2 films were scanned with an EPSON 11000XL Pro. The images were acquired in 24 bit colour (RGB) mode, with a resolution of 300 dpi, and saved in an uncompressed TIFF format. The calibration curve extrapolated with a polynomial of 3rd order was used to analyse the dose distribution from the EBT2 films.

Using EBT2 film dosimetry to determine the dose distribution in the area of Bragg peak or SOBP was questioned by [13, 14] who reported under-response in the Bragg peak region and similar effect in the distal part of the SOBP. Due to the occurrence of high LET particles at sharp dose gradient the so called quenching effect may appear. Unlike in most of proton therapy facilities, the beam line of the JINR Phasotron is characterized by a relatively wide Bragg peak [15], therefore it sustain an accurate response of the EBT2 in dose distribution measurements. Moreover, in our study, the LET spectra of modified beam by ridge filter, exhibits a very low value. Taking into account the properties of our beam, the quenching effect is improbable to influence significantly our results.

TED. Irradiated detectors were etched in a 5N NaOH solution at 70°C, with an etching time of 18 hours [9, 10]. The tracks have been imaged using a high-speed imaging microscope HSP-1000 and analysed semi-automatically using the software HspFit, which can evaluate major and minor axes of the etched tracks created by particles with LET, in the range of about 7 keV/ μm to more than 1000 keV/ μm . In the experiments using TEDs, the dose was decreased 10 times (0.25 Gy) to satisfy the necessary condition that etched tracks cannot overlap.

3 Results and Discussion

In this study, we have used a sophisticated anthropomorphic phantom to assess the effect of metallic dental implants on the delivered dose for realistic treatment plans. The regions of interest in the experiment presented are characterized by an extremely heterogeneous area: high density titanium implants alongside teeth and air.

The vertical beam profile (figure 2, right side) of the simulated plan exhibits the same shape as does the experiment. When we compare the horizontal beam profiles (figure 2, top) we noted a high level of inaccuracy behind the implants caused by the heterogeneous structures.

For the target with the implants located in the entrance region, we have chosen a more difficult irradiation plan to quantify the errors introduced by the presence of the implants in the beam trajectory (see figure 3). Our motivation for irradiating the target from this direction was to obtain a detailed comparison between experimental and calculated data behind the implants and high density teeth. We detected differences in the horizontal profile of the proton beam (see figure 3, top), caused by the very high density inhomogeneous media located in the beam's path.

Gamma index analysis. To quantitatively determine differences in the isodose distributions (measured and calculated), the gamma index was calculated for each case. The gamma index takes into account both the dose and geometry, and makes it possible for researchers to quantitatively compare the isodose distributions [12]. Our tolerance criterion for geometric accuracy was 3 mm with a 3% tolerance for dosage (see table 1). The gamma index for the first target, 84.3%, is a consequence of the air gap behind the target. If we wouldn't take into consideration the dose distribution in the air, the result will improve. Despite this, the calculated results obtain using RayTreat are in good agreement with the measurements for both irradiation plans.

In this study, using the EBT2 films, we investigate the global effect of the treatment in presence of dental implants. To better estimate the local effect of the grade 4 titanium into the treatment plan, we placed near the isocenter TED detectors which allow to evaluate microdosimetric features

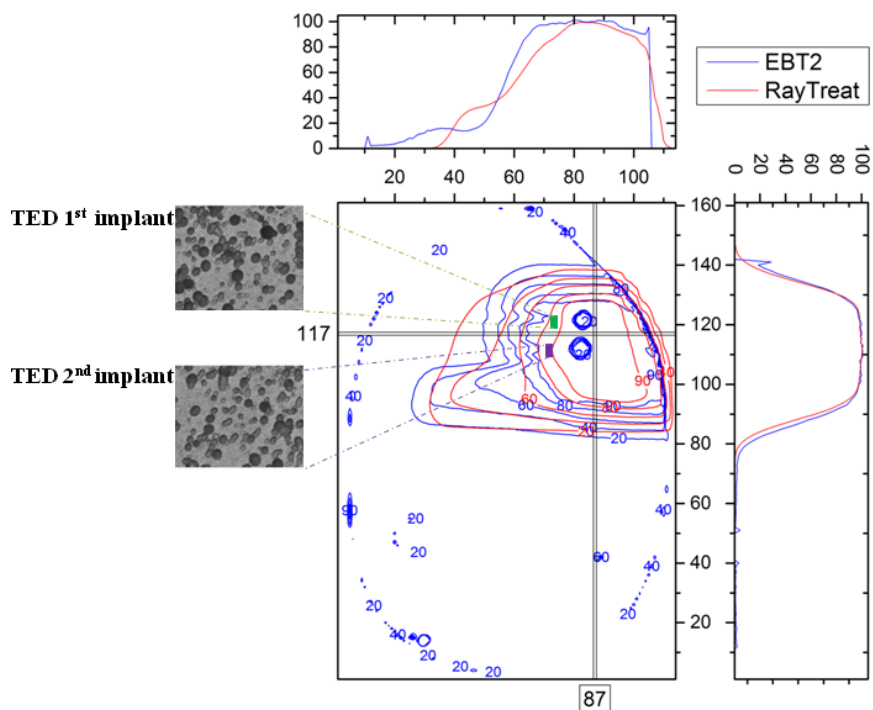


Figure 2. Comparison of 2D dose distribution of a proton beam simulated in a 3D treatment planning system (RayTreat) and measured with EBT2 films (EBT2). Vertical and horizontal beam profiles at isocentre are presented. Identification of the TED's position in the dose curves plans.

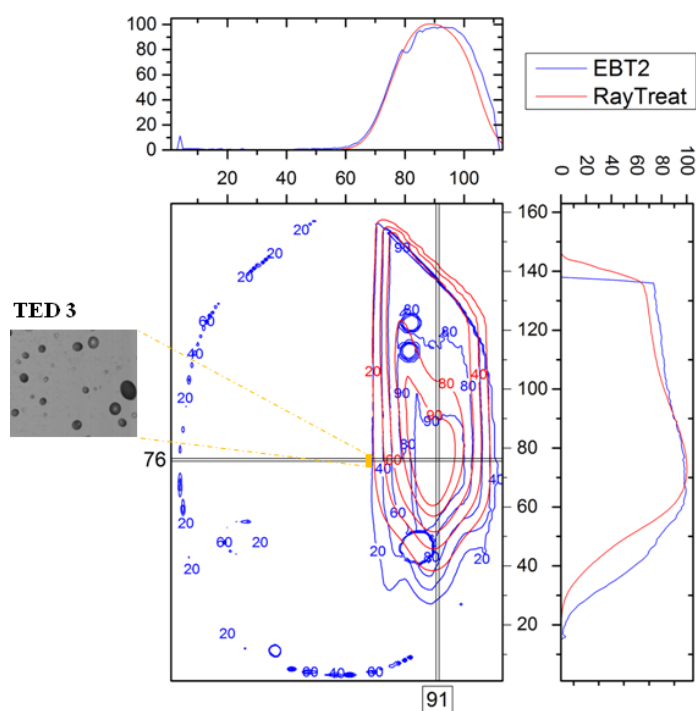


Figure 3. Comparison of 2D dose distribution of proton beam simulated in RayTreat and measured with EBT2 films (EBT2). Vertical and horizontal beam profiles at isocentre are presented. Identification of the TED's position in the dose curves plans.

Table 1. Gamma index analysis, accuracy 3 mm and 3% for high dose (>90%).

Target	Gamma index (3 mm, 3%) EBT2&RayTreat
implants located in SOBP region	84.3%
implants located in entrance region	86.4%

of radiation field. The LET spectra behind the implants was studied as an additional information, due to the limitations of film dosimetry.

We detected many primary protons and secondary particles with LET between 7 keV/ μ m and 1000 keV/ μ m corresponding to the tail of the Bragg peak in the isocentre region (figure 4, A) behind the implants located in the SOBP region. In the case of irradiation through implants located in the entrance region of the Bragg curve, we detected an increase in the absorbed dose outside the target (see figure 4, B, TED 3). In the LET spectra near the isocentre, (detector TED 3), we detected a very high number of particles with LET between 10–200 keV/ μ m, presumably corresponding to the scattered particles caused by the air gap inside the phantom, which interferes with the irradiation plan (see figure 4, B).

Our results show evidence that these dental implants cause dose distribution inaccuracies in the treatment planning. This can be a major factor in reduced tumour control for patients with dental implants. Although the dose errors are slightly below the limits, they can be reduced by applying several radiation fields [7] and by optimising the 3D TPS. In general, the 3D TPS are based on the pencil-beam dose calculation algorithm, which does not consider the interaction of titanium with the proton beam [11].

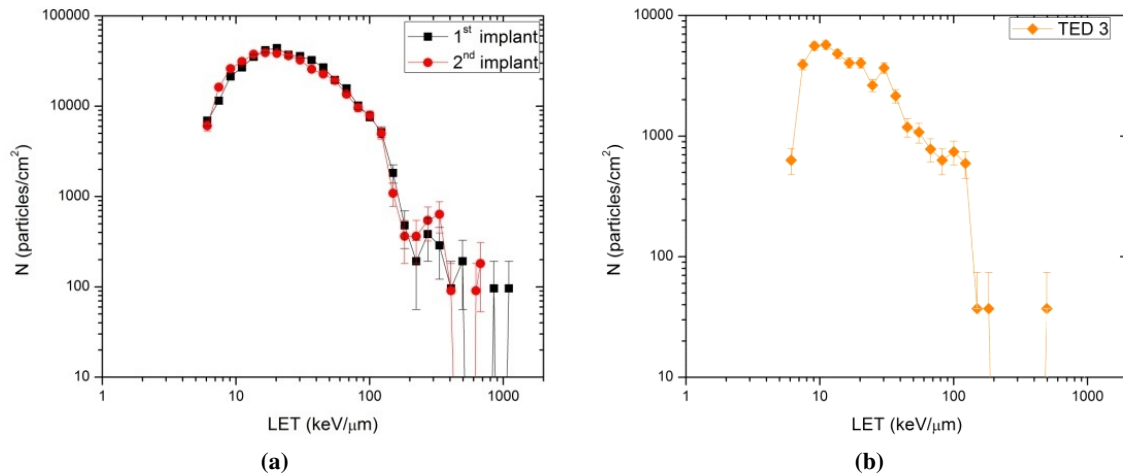


Figure 4. LET spectra of primary and secondary particles behind the first and the second implant localized in the SOBP region (A) and LET spectra of particles outside the target (B), when the implants are located in the entrance region of the Bragg curve.

4 Conclusion

In summary, the accuracy of dose calculation algorithms in the presence of titanium alloy has been investigated by measuring the dose delivered to an anthropomorphic phantom containing two titanium dental implants.

The results we obtained with EBT2 films indicate that the uncertainties introduced by the clinically planned dose distribution are beyond accepted clinical limits when treating patients with implants. Our findings allow us to continue the optimisation process of our custom-made 3D TPS, RayTreat, which shall lead to an improvement of the dose calculation in the presence of heterogeneities along the beam path. The treatment of tumours treated across titanium implants needs to be studied carefully, due to the presence of a high number of secondary particles with high LET in the isocentre, in addition to possible scattered particles in the dental implants.

The increase of LET is accompanied by the increase of the relative biological effectiveness (RBE) above internationally accepted proton RBE value of 1.1, and the increase of the absorbed dose [16]. By examining the LET spectra in figure 4, A, we may conclude that the scattering of the therapeutic proton beam inside the dental implant causes the increase of particles with LET higher than 100 keV/ μ m, which may lead to the increase of the RBE value from standard consideration.

The applied dosimetry techniques are also potentially suitable for investigation and characterisation of the beam quality produced by an ion-laser accelerated beam, and for 2D and 3D dose verifications in either air or anthropomorphic phantoms.

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