Original Article

A Monte Carlo study on dose perturbation due to dental restorations in a 15 MV photon beam

ABSTRACT

Aim: The main purpose of this study is to evaluate the effect of dose perturbation due to common dental restoration materials in the head and neck radiotherapy with a 15 MV external photon beam.

Setting and Design: Teeth with three dental restorations such as tooth filled with Amalgam, Ni-Cr alloy, and Ceramco were simulated by MCNPX Monte Carlo code. In this simulation, the dental materials were exposed by a 15 MV photon beam from a Siemens Primus linac, inside a water phantom.

Materials and Methods: A Siemens Primus linear accelerator and a phantom including: tooth only, tooth with Amalgam, tooth with Ni-Cr alloy, and tooth with Ceramco were simulated by MCNPX Monte Carlo code, separately. The percentage dose change was evaluated relative to dose in water versus depth for these samples on the beam's central axis. The absolute dose by prescription of 100 cGy dose in water phantom at 3.0 cm depth was calculated for water, tooth, tooth with Amalgam, tooth with Ni-Cr alloy, and tooth with Ceramco.

Results: The maximum percentage dose change is related to tooth with Ni-Cr alloy, tooth, tooth with Ceramco, and tooth with Amalgam with amounts of 7.73%, 6.95%, 4.7%, and 3.06% relative to water at 0.75 cm depth, respectively. When 100.0 cGy dose was prescribed at 3.1 cm, the maximum absolute dose was 201.0% in the presence of tooth with Ni-Cr alloy at 0.75 cm.

Conclusion: Introduction of the compositions of dental restorations can improve the accuracy of dosimetric calculations in treatment planning and protect the healthy tissues surrounding teeth from a considerable overdose.

KEY WORDS: Dental restoration, dose distribution, dose perturbation, external beam radiotherapy, photon beam

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INTRODUCTION

Head and neck cancers start in the tissues and organs of the head and neck. They include cancers of the throat, lips, mouth, nose, and salivary glands. They account for approximately 4fv% of all malignancies in the United States.[1] Radiotherapy, surgery, and chemotherapy are the common modalities for the treatment of head and neck cancer. These days most patients treated by radiotherapy have nonremovable dental restorations. These common dental restorations with different compositions result in photon dose perturbation before and beyond the teeth. When a photon beam strikes a high-density material, most photons are scattered in various directions, especially backward. This backscattering radiation can cause acute and long-term effects on healthy tissues during head and neck cancer radiotherapy.[2]

To have an accurate treatment plan requires all information about the patient, including information about prostheses, dental restorations, etc. When these external materials are placed in the path of a photon beam, it causes perturbation in the dose distribution and damage to healthy tissues. The American Association of Physicists in Medicine in report No. 81 recommended to use beam arrangements that avoid direct exposure to prosthesis and dental restorations.[3] In most cases, these prostheses are located very close to the target volume, especially were dental restorations are placed in a small area. In common treatment planning systems (TPSs), only electron

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densities such as inhomogeneities are introduced whereas the compositions of these external materials have to be taken into account. Inaccurate dose deliveries to the tumor and dose discrepancies are a consequence of ignoring dental restorations and prostheses, including their compositions and their effects on the dose distribution. There are several factors that can affect the size of this dose perturbation due to high-density materials such as characteristics of the radiation field, compositions, and design of these external materials. The main reason of error in TPSs is the inability to model changes in production of charged particles, and photon backscattering was the photon beam passes through this high *Z* media to reach the tumor.[4-7]

Some clinical studies have been performed on tumors such as mandible, maxilla, oral cavity, various types of squamous cell carcinoma, and cancer of tongue during radiotherapy and side effects of radiation associated with head and neck cancer. These studies are trying to minimize oral morbidity for these patients and improve their quality of life. Dose distortion in radiotherapy due to the dental restorations was evaluated previously.[8-14] For instance, Shimamoto *et al*.[8] measured scattered dose resulting from nine metal dental fillings using a single-field technique, three-dimensional conformal radiation therapy, and intensity-modulated radiation therapy with a 4 MV photon beam of a linear accelerator. In the single-field technique with gold sample, the largest dose increase was observed up to 19.3%. In another study, dose distribution for four commercial dental implants with two methods of pencil beam convolution and Monte Carlo simulation for 6 MV photon beam was investigated by Çatli.[9] They compared both results and showed the Eclipse TPS cannot precisely account for the backscatter radiation due to these dental prostheses. Risk of dose enhancement on the surrounding tissues of titanium dental implants with 6 MV photon beam was studied by Friedrich *et al*.[10] They found out the titanium implant can cause significant radiation backscattering upstream the implant. De Conto *et al*.[11] evaluated the distortion of 6 MV photon dose distribution and electron contamination due to dental prostheses. They found that a crown has greater backscatter increase than Amalgam with values of 23.8% and 1.4%, respectively. Abdul Aziz *et al.*[12] worked on interfaces of high-density inhomogeneities. Materials such as Amalgam, tooth only, and homogeneous phantom were evaluated by a 9 MeV therapy electron beam. As a result, the dose enhancement causes dramatic effects on patient's oral health during and after treatment. The authors in their studies have suggested inserting a shield with low-density material to protect healthy tissue and attenuate the backscattered dose. In a similar case, Chin *et al.*[13] studied a 10 MV photon beam and ^{60}Co photon beam in the presence of different dental restorations. They found out that a low atomic number material or air gap with 4 mm thickness can attenuate this backscattering dose. Reitemeier *et al.*[14] have studied the effects of backscattering and absorption of 6 and 15 MV photon beams due to four dental materials. These high atomic number materials included gold alloy, pure titanium, Amalgam, and a synthetic material. They also suggested using 3 mm thickness of synthetic stent to decrease the damage from backscattered radiation.

These days many different linac machines are used to treat cancer patients, and they work in various energies and have different photon spectra and dose distributions. Fifteen MV photon therapy beam of the Siemens Primus linac is one of these machines which are used in some countries for the treatment of head and neck cancer. It should be noted that previous authors have studied the dose distribution of low photon energies in medical linacs in the presence of dental restorations. In addition, a few cases of head and neck cancer are treated with higher energy photons such as 15 MV to better achieve dose uniformity and deeper penetration. Although photon with high energies are not conventional in the treatment of head and neck cancers, they can be used in some cases such as a lateralized lesion of the oropharynx, sinuses and in patients in whom tumor has spread into the posterior fossa.[15] As it mentioned before, some authors have also utilized high energy photons to the investigation of effects dental prostheses and implants in head and neck cancer treatment.[14,16,17]

Three commercial dental restoration materials which were evaluated in this study are Amalgam, Ni-Cr alloy, and Ceramco. The aim of this study was to compare dose distributions of Siemens Primus 15 MV photon beam in the presence of tooth, tooth with Amalgam, tooth with Ni-Cr alloy, and tooth with Ceramco has been done.

MATERIALS AND METHODS

Monte Carlo simulation validation of linac

For dosimetric studies, a validated model of a Siemens Primus linac (Siemens AG, Erlangen, Germany) which was described in a previous study was used.[18] All components of the 15 MV photon beam and linac head were simulated by MCNPX version 2.6 code in that study. The geometry and dimensions were provided by manufacturer information.[19,20] A water phantom was placed at 100 cm source to surface distance (SSD) to score the 15 MV photon dose with 6 cm × 6 cm, 10 cm × 10 cm and 18 cm × 18 cm field sizes. Percentage depth dose and dose profiles were calculated in the water phantom using MCNPX code. In that study, to validate the simulation of the Siemens Primus linac, the experimental measurements of dose values were done in the water phantom of 50 cm × 50 cm × 50 cm in dimensions by a Wellhofer-Scanditronix dosimetry system (Wellhöfer, Uppsala, Sweden) with a diode detector on a Siemens Primus linear accelerator in 15 MV photon mode. Finally, the simulation results obtained were compared with the experimental data and good agreement was observed, and the discrepancies were <5%.[18]

Effect of tooth and dental restorations

To investigate the effect of high-density inhomogeneities on the 15 MV photon beam of a Siemens Primus linac, three commercial dental restorations were considered. MCNPX

MCNPX Monte Carlo code (version 2.6.0, Los Alamos National Laboratory, US) was used.[21] These materials include Amalgam, Ni-Cr alloy, and Ceramco, which are currently used in dentistry. The effect of these materials was evaluated for 10 cm × 10 cm field and SSD of 100 cm. All these samples which were simulated independently in this study include tooth, tooth filled with Amalgam, tooth filled with Ni-Cr alloy, and tooth filled with Ceramco. The healthy tooth consists of a crown with dimensions of 0.8 cm × 0.5 cm × 0.8 cm which is composed of 20.0% enamel and 80.0% dentine. A cube of 0.8 cm × 0.5 cm × 0.8 cm was placed as the root, inferior to the crown. In the case of a complete healthy tooth filled with restoration materials, the configuration is 50% root, 20% crown, and 30% restoration materials. Table 1 gives the compositions and densities of the various materials used in the study.[13,21,22] Three teeth included two healthy teeth on either side and a healthy tooth or tooth with dental restoration in the middle, all in the water phantom. The distance between the teeth and the top surface of the water phantom was 1 cm and middle tooth was simulated perpendicular to isocenter of 15 MV X-ray beam. The complete geometry of these three teeth is presented in Figure 1. This design of the photon beam and tooth depth was based on radiotherapy of head and neck cancer. The clinical examples of this treatment are oral cavity, mandible, cancer of the tongue, and various types of squamous cell carcinoma. In all of these treatments, by various fields and energies, teeth and dental restorations can be located in the path of photon beam.

To show the effect of the dental restorations on the dose distribution of a 15 MV photon beam in head and neck cancer therapy, two points before and five points after the middle tooth were considered. To calculate the dose distribution, the real phantom geometry was simulated. This geometry was considered as cylinders with 0.25 cm radius and 0.65 cm height in these points to score the dose values. To perform this calculation, two programs were run. First, the number of histories was 2×10^9 and a source surface card was utilized at 19.7 cm from source up to above Y jaws to score 640×10^9 particles. In the second input file, this number of particles was read as a source surface read card.

The photon energy deposition was calculated in the scoring cells using tally of *F8. This tally describes the energy deposition

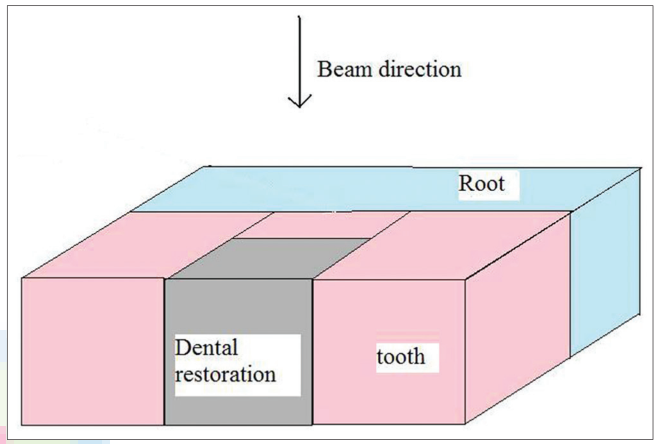

Figure 1: A schematic view of the water phantom and tooth with dental restorations used in the simulation. The tooth is located at distance of 1 cm from top of the water phantom surface. The coordination of the reference point are (0 cm, 0 cm, −106.0 cm)

Table 1: Mass densities and compositions of dentine, enamel, root, amalgam, Ni-Cr alloy and Ceramco

Element	WF (%)					
	Dentine (ρ=2.180 g/cm³)	Enamel (ρ=2.970 g/cm³)	Root (ρ=2.338 g/cm³)	Amalgam (ρ=8.000 g/cm³)	Ni-Cr alloy (ρ=7.900 g/cm³)	Ceramco (ρ=2.600 g/cm³)
H	3.080	0.980	2.660	-	-	-
Be	-	-	-	-	1.650	-
C	11.300	1.470	9.334	-	-	-
N	2.500	0.130	2.026	-	-	-
O	36.140	41.920	37.296	-	-	38.965
F	0.020	0.010	0.018	-	-	-
Na	0.200	0.600	0.280	-	-	8.3164
Mg	1.100	0.400	0.960	-	-	-
Al	-	-	-	-	2.000	14.646
Si	-	0.003	0.001	-	-	15.243
P	15.000	17.500	15.500	-	-	-
Cl	0.030	0.250	0.074	-	-	-
K	0.070	0.300	0.116	-	-	7.073
Ca	30.500	36.400	31.680	-	-	-
Cr	-	-	-	-	15.000	-
Fe	-	0.003	-	-	-	-
Ni	-	-	-	-	75.000	-
Cu	-	0.010	0.002	11.800	-	-
Zn	0.018	0.016	0.0180	1.000	-	-
Mo	-	-	-	-	5.000	
Ag	-	-	-	69.300	-	-
Sn	-	-	-	17.900	-	15.755
Ti	-	-	-	-	1.350	-

WF=Weight fraction

in each cell with unit of MeV. The energy cut off for electrons and photons was 10 keV, and no other variance reduction technique was defined. Because of high uncertainties, ten programs were run for a dental restoration then the uncertainties were combined to reach an acceptable uncertainty level. Random seed numbers of the input files were different to have a distinct run. Therefore, the average dose in each tally, based on dose calculations in ten programs, was obtained. The maximum Monte Carlo type A uncertainty in the tally cells was 5.1%.

Two quantities investigated in this study were percentage photon dose change and absolute dose. The values of these quantities were compared for various dental restoration materials and different depths with 15 MV photon beam. To calculate the percentage photon dose with and without dental restorations the following formula was used:

$$\text{Percentage dose change} = 100 \times \frac{(D_2 - D_1)}{D_1} \quad (1)$$

D_1 is defined as the photon dose in the absence of the tooth at a certain depth (open field) and D_2 is defined as the dose at the same depth in the presence of a tooth with dental restoration. In such cases, positive or negative sign of percentage dose change indicates an increase or decrease in dose in the presence of the sample compared to the open field, respectively. Another interesting quantity for medical physicist is absolute dose (cGy/100 Monitor Unit [MU]). This quantity introduces dose in each point relative to prescription of 100 cGy (100 MU) dose in the water at a depth of 3.0 cm as the reference point. It should be noted that this maximum depth dose depends on the energy of the 15 MV photon beam. As it was mentioned before, this high energy beam is prescribed to obtain better penetration for some special cases or obese patients.

Table 2: Percentage dose change relative to dose in water in presence of tooth, tooth with amalgam, tooth with Ni-Cr alloy and tooth with Ceramco

Depth (cm)	Tooth	Tooth with amalgam	Tooth with Ni-Cr alloy	Tooth with Ceramco
0.25	−5.28	−0.36	5.48	1.28
0.75	6.95	3.06	7.73	4.70
2.10	−12.02	−23.50	−14.10	−8.56
3.00	−6.23	−12.80	−14.45	−9.36
4.00	−0.31	−13.10	−11.32	−5.29
5.00	0.71	−6.09	−8.04	−1.38
6.00	−1.98	−11.30	−12.44	−3.28

Table 3: Absolute dose (cGy) in water and in presence of tooth, tooth with Amalgam, tooth with Ni-Cr alloy and tooth with Ceramco

Depth (cm)	Water	Tooth	Tooth with amalgam	Tooth with Ni-Cr alloy	Tooth with Ceramco
0.25	170.00	179.00	169.00	179.00	172.00
0.75	187.00	200.00	193.00	201.00	196.00
2.10	149.00	131.00	114.00	128.00	136.00
3.00	126.00	118.00	110.00	108.00	114.00
4.00	118.00	119.00	103.00	105.00	112.00
5.00	101.00	101.00	94.60	92.60	99.40
6.00	100.00	97.90	88.60	87.50	96.60

These results were calculated in the case of prescription of 100 cGy (equals to 100 MU) dose at depth of 3.0 cm in the water phantom

RESULTS

The photon percentage dose change for a tooth with dental restorations such as Amalgam, Ni-Cr alloy, and Ceramco for 10 cm × 10 cm 15 MV photon radiation field is listed in Table 2. In our study, two healthy teeth are placed on either side of a healthy tooth or a tooth filled with these three dental restorations. These data for the mentioned materials are also plotted at different depths in Figure 2. The position of the tooth is specified by two lines placed in 1 cm to 1.8 cm in the Figures of 2 and 3. The absolute photon dose (cGy) for these materials are listed in Table 3. These data were calculated for water, tooth, tooth with Amalgam, tooth with Ni-Cr alloy, and tooth with Ceramco in which 100 cGy photon dose was prescribed to the depth of 3.0 cm in the water phantom without tooth. In Figure 3, the absolute dose values are depicted for these mentioned materials versus depth in water.

DISCUSSION

In the present study, the effect of dental restorations such as Amalgam, Ni-Cr alloy, and Ceramco on 15 MV photon dose distributions was studied by Monte Carlo. Figure 2 shows the relationship between the percentage dose change and the depth for various dental restorations. This figure implies that this quantity is not constant and depends on depth in phantom. In this plot, the percentage dose change arises with increase of depth up to the front of tooth surface. The obtained results of percentage dose change using the Monte Carlo method are presented in Table 2. The maximum difference of percentage dose change of these inhomogeneities with water are at 7.73% for Ni-Cr alloy, 6.25% for tooth, 4.7% for Ceramco and 3.06% for Amalgam distance of 0.75 cm. These percentage dose changes for dental materials were calculated relative to the open field dose. This dose increase is due to the backscatter of photons from high-density materials behind the high-density materials. When photon high-dose radiation reaches the dental restoration materials, photons of the dental restorations are backscattered. In this high photon energy range, the Compton process is dominant. As it is known Compton process does not depend on atomic number. This overdose before the water-tooth interface can damage the neighboring soft tissue and cause negative side effects.

At the points beyond the tooth, dental restorations can cause attenuation that the other studies have confirmed. When 15 MV photon beam passes through the high-density materials some of photons deposit their energy inside these materials. Figure 2 shows the percentage dose change of these inhomogeneities with water starts with fall off at 2.1 cm. In this depth, the maximum underdosage is related to Amalgam with −23.5% and after that Ni-Cr alloy, tooth, and Ceramco with values of 14.1%, 12.02%, and 8.56%, respectively. After

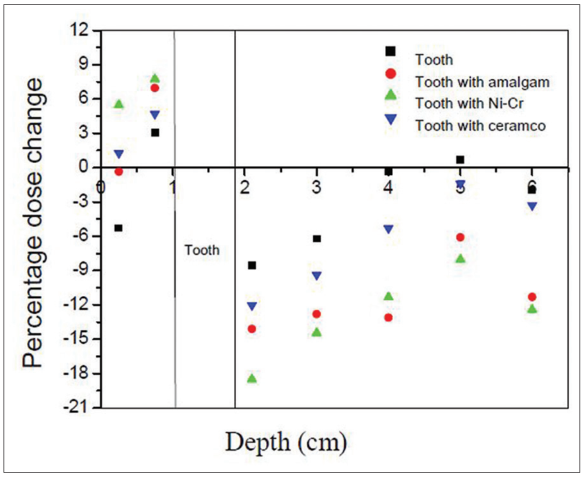

Figure 2: Percentage dose change relative to dose in water versus depth (cm) in presence of tooth, tooth with Amalgam, tooth with Ni-Cr alloy and tooth with Ceramco

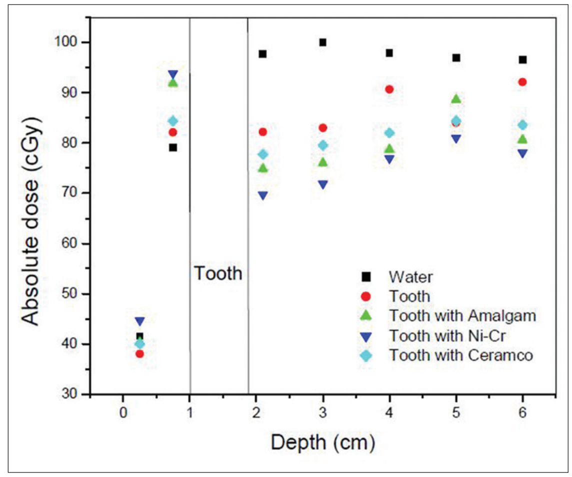

Figure 3: Absolute dose (cGy) versus depth (cm) in water phantom obtained for samples of tooth, tooth with Amalgam, tooth with Ni-Cr alloy and tooth with Ceramco. Absolute dose of 100 cGy (100 MU) was prescribed at 3.0 cm depth

the sample, the trend of curves for these four materials rises after a sharp fall of up to further depths and then decreases. For example, the maximum values of percentage dose change are observed at the 5 cm depth for tooth only, tooth with Ceramco, tooth with Amalgam, and tooth with Ni-Cr alloy with values of 0.71%, −1.38%, −6.09%, and −8.04%, respectively. In general, after the sample there is an underdosage of high-density materials rather than water dose. The present study's findings demonstrate the change of dose distribution varies with the depth for the various high-density materials.

Results of the absolute dose (cGy/100 MU) for the various dental restorations in a 15 MV photon beam are listed in Table 3. As it was mentioned before, a point is considered as a reference in which 100 cGy (100 MU) dose in the water at depth of 3.0 cm has been prescribed. According to this table, behind the tooth considerable absolute dose can be observed especially at distance of 0.75 cm. In the evaluation of absolute dose in this region, Ni-Cr alloy, tooth, Ceramco, Amalgam, and water have the highest absolute dose of 101, 100, 96, 93, and 87 cGy with prescription of 100 cGy dose in water at 3.0 cm, respectively. As a result of the comparison, for all high-density materials after the sample, there is a decrease at 2 cm depth due to attenuation of photon energy. These findings illustrate that after the tooth-water interface the absolute dose starts with values of 49 cGy for water, 36 cGy for Ceramco, 31 cGy for tooth, 28 cGy for Ni-Cr alloy, and 14 cGy for Amalgam, respectively. As it was mentioned before, in front of high-density materials, the trend of the curve decreases to depths of 6 cm, therefore, the absolute dose is lower for Ni-Cr, Amalgam, Ceramco, and tooth with amount of 87.5, 88.6, 96.6, and 97.9 cGy with prescription of 100 cGy dose in water at this depth.

A comparison of the percentage dose change in four different media such as tooth, Amalgam, Ni-Cr alloy, and Ceramco for 6 and 15 MV photon beams are presented in Figure 4. From these plots, it is obvious that for different materials in the different energies all plots follow a similar trend. At the beginning, where the beam entering the media up to the water/high-density material interface at 1 cm depth, the backscatter dose would increase with a sharp peak. Whereas after the interface of high-density material/water and beyond tooth for all the plots, it can be seen that the percentage dose changes are almost negative or have a minor value relative to the dose in the water. These results emphasize the risk to healthy tissues before the tooth and tooth with restoration materials. To interpret the results for the treatment of head and neck cancer with external photon beam in a precise way, a comparison between the present study and other studies would be interesting.[13,14,23,24] Many authors investigated solutions to decrease the negative effects of backscattering dose. In similar cases, Farahani *et al*.[23] and Reitemeier *et al*.[14] suggested to use an adequate low Z material with thickness of approximately 3 g/cm^2 behind the tooth to attenuate the backscattered dose. In another study Chin *et al*.[13] worked on different phantom configurations even air gap between tissue and tooth. They found that it does not need any specialized shield, but with 4 mm of cotton roll soaked in water, buccal mucosa will be reinforced and by this way the backscattered dose is completely attenuated.

For evaluation of energy effects on tooth and dental restorations, the Monte Carlo results of percentage dose change for 15 MV photon beam are compared to the results of percentage dose change for 6 MV photon beam. Azizi *et al.*[24] studied the effects of teeth and these dental restorations on 6 MV photon dose distributions in Siemens primus linac. All conditions of both simulations such as linac geometry, dimension, composition of phantom, and dimension of voxel to score dose were the same. In Figure 4, the comparison of percentage dose changes for healthy tooth, tooth with Amalgam, tooth with Ni-Cr alloy, and tooth with Ceramco

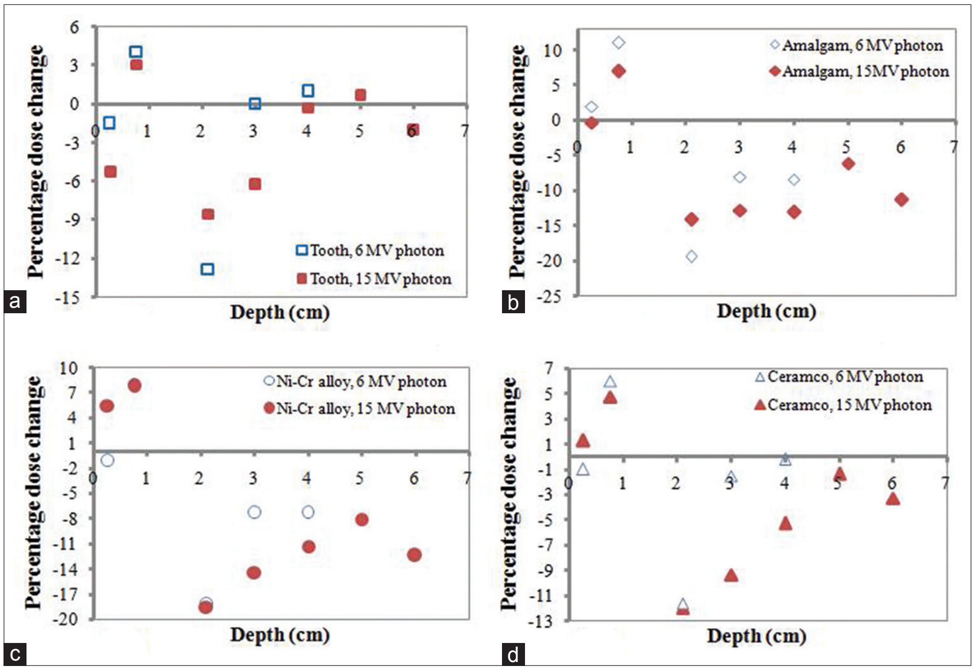

Figure 4: Percentage dose change for tooth only (a), tooth with Amalgam (b), tooth with Ni-Cr alloy (c) and tooth with Ceramco (d) with 6 and 15 MV photon beam versus depth inside water phantom

in this study and previous study has been presented. From Figure 4 it is clear that for four high-density materials, plots follow a general trend in this way that in two energies the curves rise up to behind the sample and after the sample start with a minimum amount then go up with increasing depth. In a detailed comparison, it is obvious that the values of percentage dose change have discrepancies for different materials and energies. These discrepancies cannot be interpreted only by Compton Effect and the main reasons for these discrepancies are differences in energy, build-up point, material, and scattering. For example, the build-u*P* values of 2.0 and 3.1 cm are for 6 and 15 MV photon beam and in our cases, the most probable photon energy is in range of 1–4 MV of photon beam. It should be mentioned that 6 and 15 MV radiotherapy photon beams are nominal beam energies and are made up of spectrum of energies with maxima no more than about 6 and 15 MeV, respectively. In general, the effect of the 15 MV photon beam are more pronounced, compared to 6 MV photon although there are some exceptions in percentage dose change. As it is known for photon particles, there are three dominant types of significant interactions such as photoelectric, Compton and pair production. It is important to note that Compton effect will have a little dependence on the atomic number *Z*, of the matter whereas the electron density (electrons per gram) will be the important factor for attenuation of a photon beam by Compton scattering. The Compton Effect is the predominant process in therapeutic energy range of approximately ~20 keV to ~20 MeV in radiotherapy photon beams.[25] As a result, the overdose values behind the sample for healthy tooth, and tooth with Ni-Cr alloy in 15 MV, and for tooth filled with Amalgam, and tooth filled with Ceramco highlights the introduction of compositions of these high-density materials in TPS.

CONCLUSION

Based on the Monte Carlo calculations in the present study, teeth and common dental restorations such as tooth filled with Amalgam, Ni-Cr alloy, and Ceramco can perturb dose distribution in radiotherapy of head and neck cancer with a 15 MV photon beam. In routine TPSs only the electron densities of inhomogeneities are considered, whereas these high atomic number materials can play an important role in overdose of healthy tissues. This dose enhancement can damage the buccal mucosa during the radiotherapy when teeth and dental restorations are placed in the path of the external exposure. These high-density materials cause some artifacts on CT images and discrepancies in TPSs and also the International Commission on Radiation Unit, and Measurement No. 24 has recommended the uncertainty in dose delivery should be $<\pm5\%$.[26] Therefore, to optimize the accuracy of TPS calculations and reduce the uncertainty, the compositions and density of high-density materials have to be taken into account. Another proposed solution to reduce this considerable overdose of radiation is the use of soft-tissue (bolus) equivalent material before the tooth. While this method may not be practical worldwide but the risk of oral diseases during the radiation therapy among head and neck cancer patients can be reduced.

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Conflicts of interest

There are no conflicts of interest.

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