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Investigating the Impact of Knee Prosthesis in Patients' Body on Radiation Dose Distribution: A Monte Carlo Approach

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ABSTRACT

Background: Metal prostheses in patients affect the radiotherapy dose distribution. Metal prostheses with high density and atomic number cause major changes in scattering and attenuation of radiation. The present study aims to assess the impact of metal knee prosthesis with various dimensions and materials on radiotherapy dose distribution.

Material and Methods: In this research, the Varian Linac and water phantom were simulated using the MCNPX code. Dose distribution of photon beam in a water phantom, with and without the presence of knee prostheses made of cobalt-chromium-molybdenum alloy, steel, titanium, and titanium alloy used in men and women was investigated using the Monte Carlo simulation.

Results: The prosthesis led to an increase in dose in comparison with cases that there was used no prosthesis. According to values of the depth dose percentage, the maximum dose increase was found to be 6.8%, 6.1%, 4%, and 4.29%, and dose reduction 41.18%, 40.66%, 37.76%, and 37.51% for prosthetics with men's knee dimensions made of cobalt-chromium-molybdenum alloy, steel, titanium alloy, and titanium, respectively. Above all, does increasing to 6.4%, 5.9%, 3.8%, and 3.94% and doses reducing to 40.87%, 40.36%, 36.94%, and 36.69 were observed in prosthetics for women. The highest amount of dose reduction for men's prostheses made of mentioned materials was found to be 48.75%, 47.7%, 45%, and 45.8%, respectively. In addition, it was 46.36%, 45.8%, 43.8%, and 43.95% for women's prostheses, respectively.

Conclusion: Material will have a significant impact if a part of the knee bone places behind the prosthesis. According to the obtained values, it is recommended to utilize prostheses made of titanium and titanium alloys for knee arthroplasty. The prosthesis can either increase or decrease dose in tumor or lead to increase dose at organs at risk.

Citation: Bayatiani M. R, Seif F, Hamidi S, Bagheri S. Investigating the Impact of Knee Prosthesis in Patients' Body on Radiation Dose Distribution: A Monte Carlo Approach. *J Biomed Phys Eng*. 2019;9(3):345-354. https://doi.org/10.31661/jbpe.v0i0.1047.

Keywords

Dose Distribution, Knee Prosthesis, Monte Carlo Simulation, Treatment Planning

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Received: 5 November 2018
Accepted: 9 December 2018

Introduction

Generally, owing to the expansion of oxidant agents in modern life, an increasing trend has been seen in the number of cancer patients, some of which have metal prostheses. According to a report from the Task Group (TG_63), 1% to 4% of cancer patients have metal prostheses which might influence the amount of dosage received in the tumoral area and also healthy tissue near the tumor [1]. Studies have shown that metal prostheses, with high atomic number and density in medical fields, impacts the dose distribution as heterogeneity [2-4]. Given the fact that the atomic numbers of metal prostheses used in different body parts such as dip joint, knee, arm are much higher than the tissues of the body; therefore, they can have a significant impact on radiotherapy dose distribution [5-9]. Various metals are used in the production of metal prostheses, including cobalt-chromium-molybdenum alloy, stainless steel, titanium alloy, and titanium [10, 11].

In radiotherapy, determining absorbed dose precisely and being adapted with the prescribed dose are important. Moreover, if there are any obstacles such as metal prostheses in beam path, dose will either increase or decrease due to changes in the absorption of primary radiation or the distribution of scattered photons [12, 13]. Megavoltage photon is used in radiotherapy; Compton scattering is a predominant phenomenon while it and beam attenuation are determined by electron density [14]. One of the methods used to investigate dose distribution in radiotherapy is Monte Carlo simulation. The Monte Carlo approach is a high accuracy simulation technique to model physical processes involved in radiotherapy with any geometry [15]. In most of the studies conducted, hip prostheses have been investigated [1, 5, 6]. However, the present study aims to assess the impact of metal knee prosthesis with various dimensions and materials on dose distribution by the Monte Carlo simulation method.

Material and Methods

In this research, 2100 *C/D* Varian Linear Accelerator, including source, target, primary collimator, vacuum window, ionization chamber, mirrors and secondary collimators, was simulated using the simulated MCNPX Monte Carlo code [16] (Figure 1).

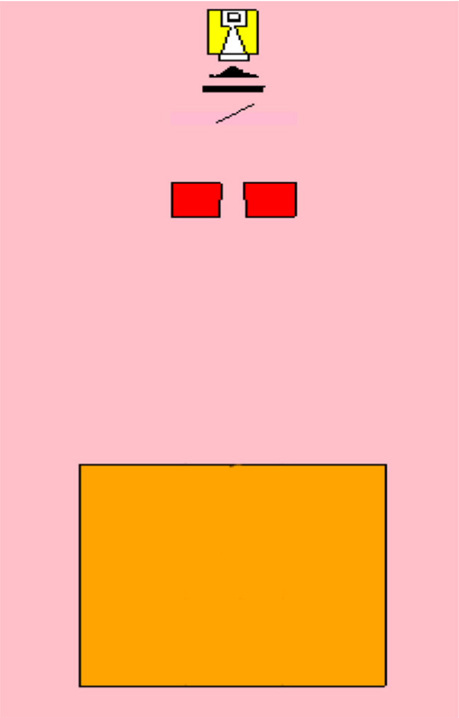

Figure 1: schematic components of Varian 2100 C/D Linac simulation.

The cut-off energies for electron and photon were assumed to be 0.511 *Mev* and 0.01 *Mev* respectively. In order to validate the simulation, (PDD) and profile curves were calculated using the Monte Carlo method at 5 cm depth, $SSD=100\ cm$ for a field with 10×10 cm^2 dimensions, in a 50×50×50 cm^3 water phantom, and the obtained results were compared with the results of practical dosimetry (Figure 2).

A cylinder with 0.5 cm radius and 30 cm height was considered to simulate PDDs on the central axis of the beam and horizontally at the reference depth of 5 cm inside the phantom. The cylinders related to PDD and profile calculations were divided into 80 and 36 cells, respectively. The program was run for 180×10^6 particles and dosage values were calculated using $*_{f8}$ in each cell. A cc13 ionization chamber with an inner radius of 0.3 cm and sensitive volume of 0.13 cm^3 manufactured by Scanditronix- wellhöfer (calibrated by SSDL center) and the Omini pro Software were utilized to conduct dosimetry.

After checking the validity of conducted

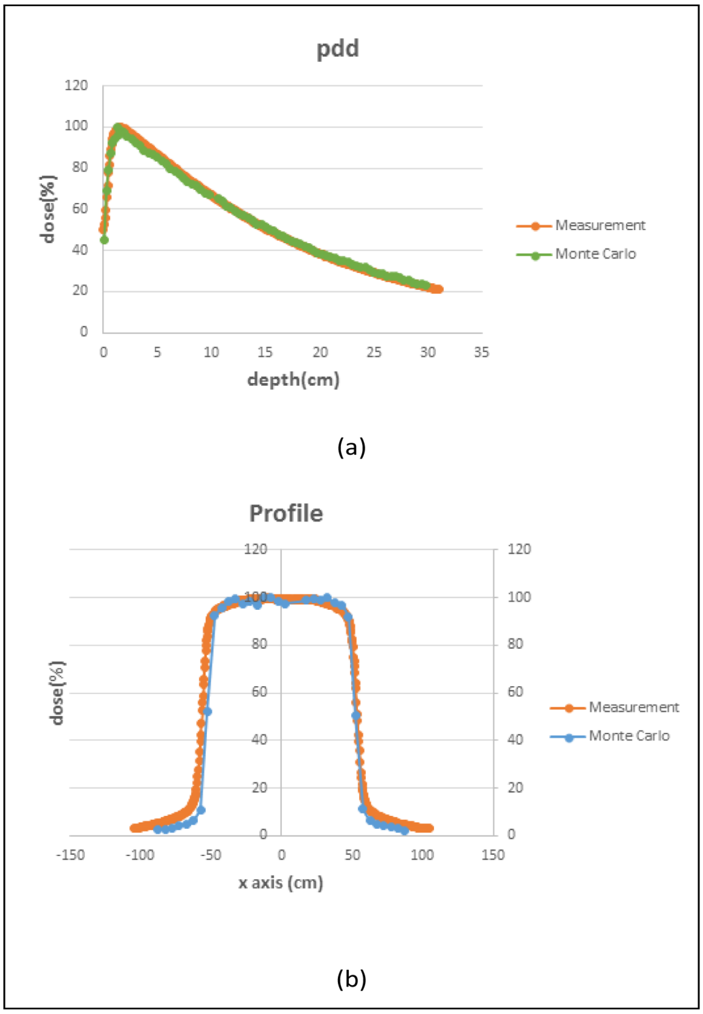

Figure 2: (a) PDDs (b) profiles calculated by MC simulation and dosimetry measurement (6MV, 10 × 10 cm^2).

simulation, knee prostheses were simulated relatively accurate with approximate dimensions of 8× 6.1× 6.2 cm^3 for men and 7× 5.5× 5.4 cm^3 for women made of cobalt-chromium-molybdenum alloy, stainless steel, titanium alloy, and titanium, with densities of 8.2 g/cm^3, 6.45 g/cm^3, 4.48 g/cm^3, and 4.506 g/cm^3 (Table 1), respectively [17-21].

Then, in order to assess the impact of prosthesis on dose distribution, PDD and profile curves (d=5cm) were calculated for women and men's prostheses with different materials at a 10×10 cm^2 filed and the results were compared in both cases, with and without prostheses.

Results

The obtained results indicated that there was a good agreement between the simulation results and those of dosimetry (the difference was about 2% for differential PDD curves (Figure 2a) and about 3.5% for the profile (Figure 2b)).

After checking the validity of simulation, in order to assess the impact of prosthesis on radiotherapy dose distribution, men and women's prostheses with four different materials were added to the simulation program according to Table 1. PDD curves were drawn for prostheses with different materials and dimensions for women (Figure 3) and men (Figure

Table 1: Elemental composition and mass density of four hip prostheses materials

Cr-Co-Mo alloy ρ= 8.20 (g/cm^3)		**Stainless Steel** ρ= 6.45 (g/cm^3)		**Ti alloy** ρ= 4.48 (g/cm^3)		**Ti** ρ= 4.506 (g/cm^3)	
Element	**WF (%)**	**Element**	**WF (%)**	**Element**	**WF (%)**	**Element**	**WF (%)**
Co	61.90	Fe	62.72	Ti	89.17	Ti	100
Cr	28.00	Cr	21.00	Al	6.20		
Mo	6.00	Ni	9.00	V	4.00		
Mn	1.00	Mn	3.60	Fe	0.30		
Si	1.00	Mo	2.5	O	0.20		
Fe	1.00	Si	0.75	C	0.08		
Ni	0.75	N	0.43	N	0.05		
C	0.35						

4). Furthermore, profile curves were drawn for prostheses with different materials for women (Figure 5) and men (Figure 6).

As seen in Figures (3) to (6), scattered electrons from the surface of the metal cause an increase in dose at the intersection of the tissue (tissue equivalent water phantom) and metal. Because of the short range of the scattered electrons, this increase in dose is only a few millimeters. Moreover, the beam passing through the metal and attenuation of the beam by it make a decrease only at the end of the metal. This decrease is shown in Figures (3) to (6) in the entire metal surface area.

The results summarized in Table 2 show an increase in PDD at the intersection of the tissue and prosthesis and also a decrease in dose at the end of the prosthesis used for men and women with different materials. However, there was no significant difference between the prostheses used for men and women.

Also, the obtained results indicate that the percentage of difference obtained between the PDD curves and profile is maximum for prosthesis used for men made of cobalt-chromium-molybdenum alloy with higher density.

Discussion

The present study investigated the influencing factor, which stemmed from the existence of prosthesis in field treatment affecting fluctuation and changes in knee dose, on dose distribution. Generally, comparing the distribution doses in the water phantom, in the presence of knee prosthesis, showed the following results:

1. An increase in dose on the interface between metal and tissue when the beam enters the metal due to scattered electrons.
2. A decrease in dose induced by beam attenuation in the metal due to atomic number and high absorption in the distal area of prosthesis.

Results of this research are in line with some studies that investigated radiotherapy doses disorder in the presence of hip prostheses using simulation. Paul et al. investigated the impact of hip metal prostheses, with dimensions of $2\times 2\times 2$ cm^3 and at the depth of 4 cm on dose distribution at the hip area in a 10×10 cm^2 field (photon 6 MV), using Monte Carlo simulation. Their results showed that different materials of metal hip prosthesis affect the radiotherapy dose distribution; however, the dose difference induced by a prosthesis made of titanium is less than stainless steel [22]. Spezi et al. investigating the effect of 4 different materials for a cylindrical hip joint prosthesis with height and diameter of 15 cm and 3 cm, respectively, on dose distribution with a 10×10 cm^2 field, showed that hip prosthesis made of cobalt-chromium alloy had the high-

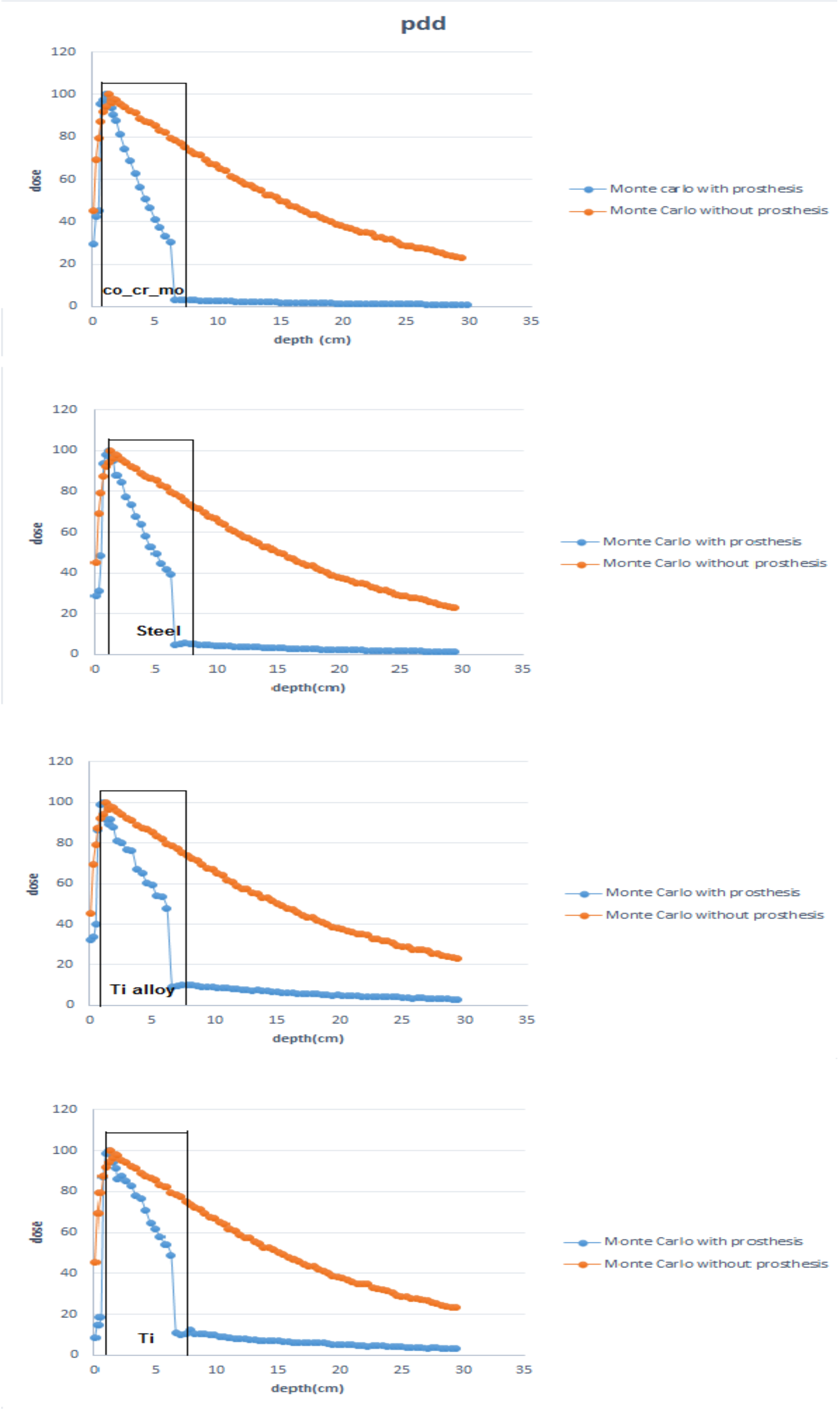

Figure 3: PDD curves calculated by MC simulation with and without women's knee prostheses made of (a) chromium - cobalt – molybdenum alloy (b), stainless steel (c) titanium alloy (d) and titanium.

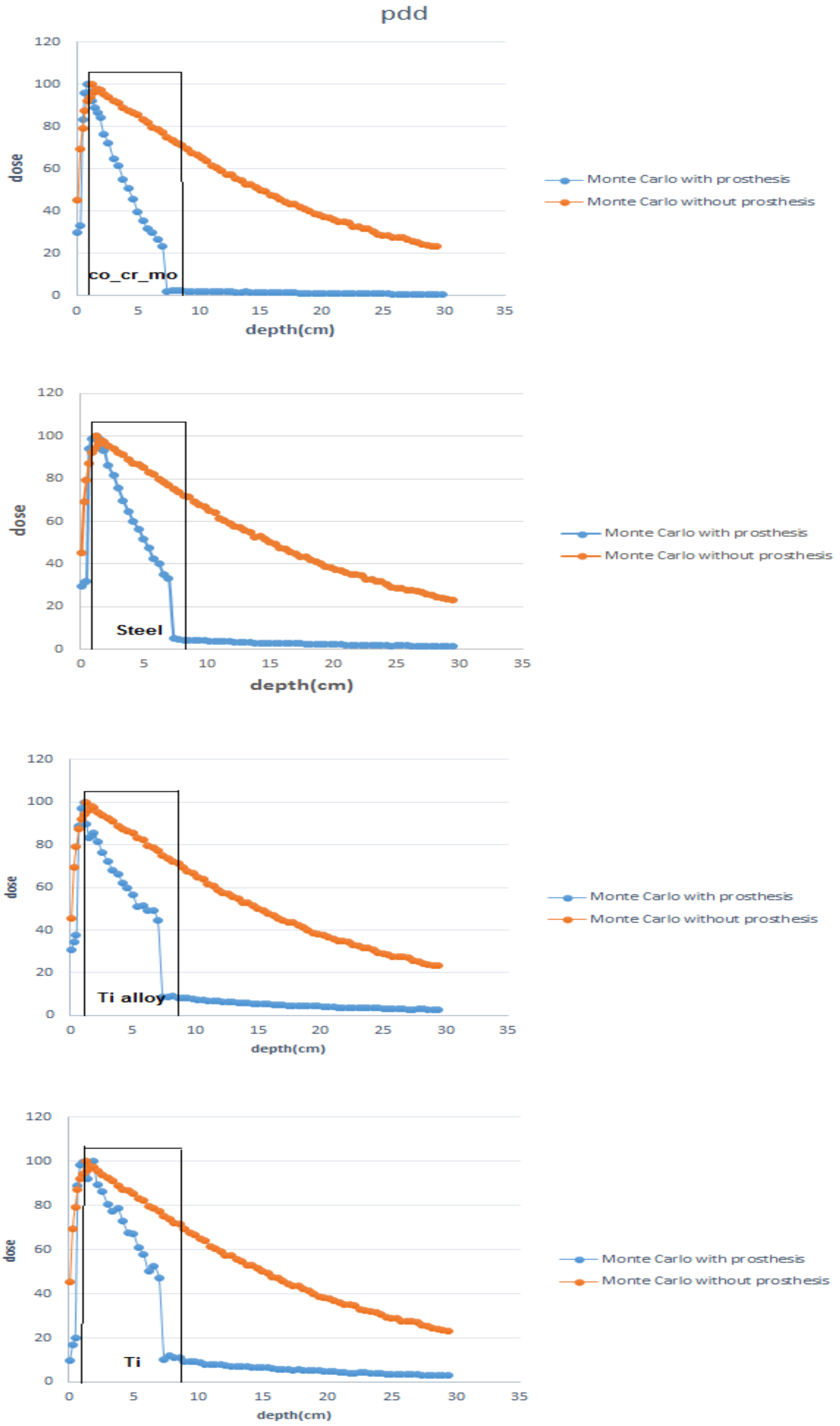

Figure 4: PDD curves calculated by MC simulation with and without men's knee prostheses made of (a) chromium - cobalt – molybdenum alloy (b), stainless steel (c) titanium alloy (d) and titanium.

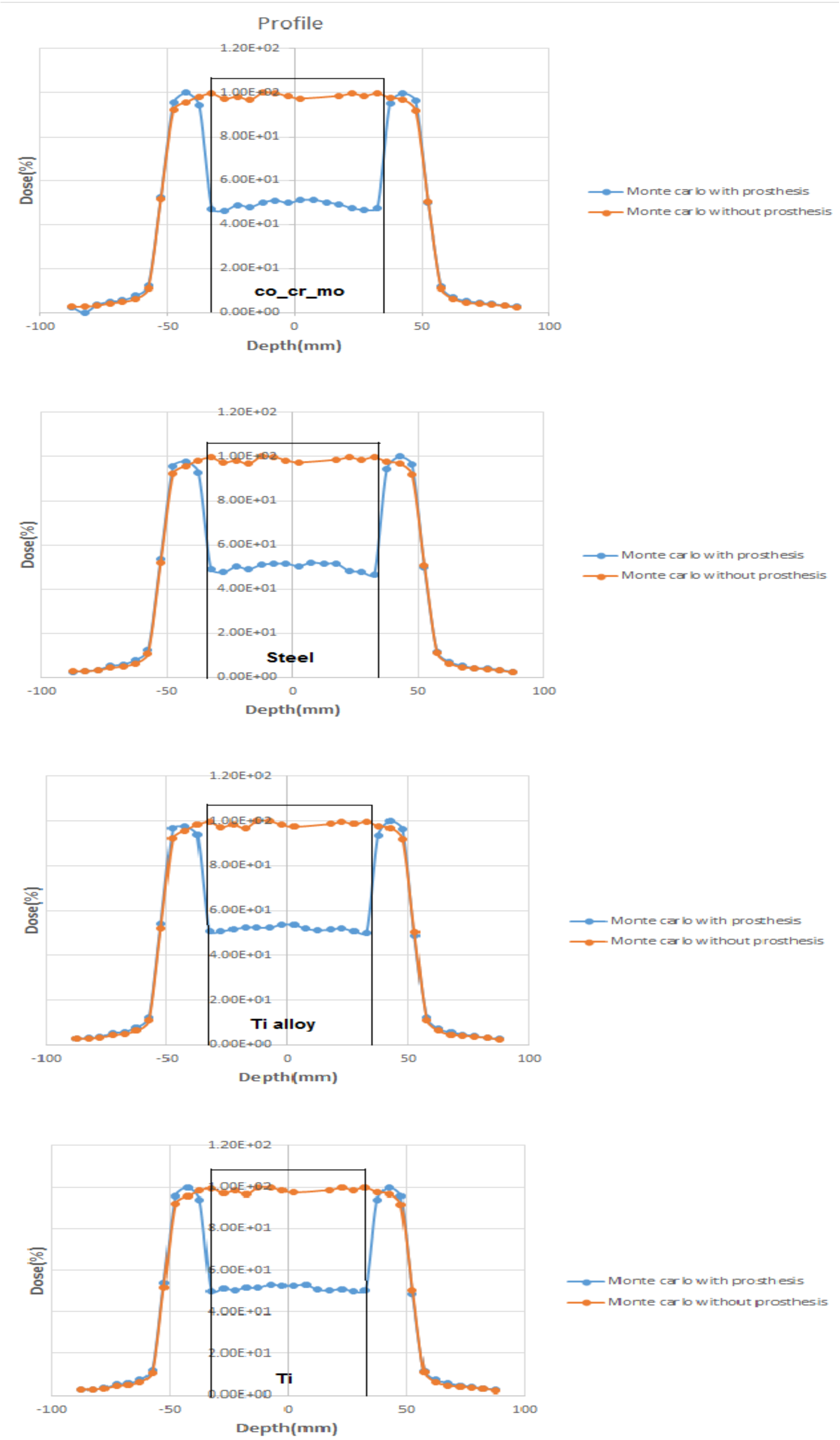

Figure 5: Dose profiles curves calculated by MC simulation with and without women's knee prostheses made of (a) chromium - cobalt – molybdenum alloy (b), stainless steel (c) titanium alloy and (d) titanium.

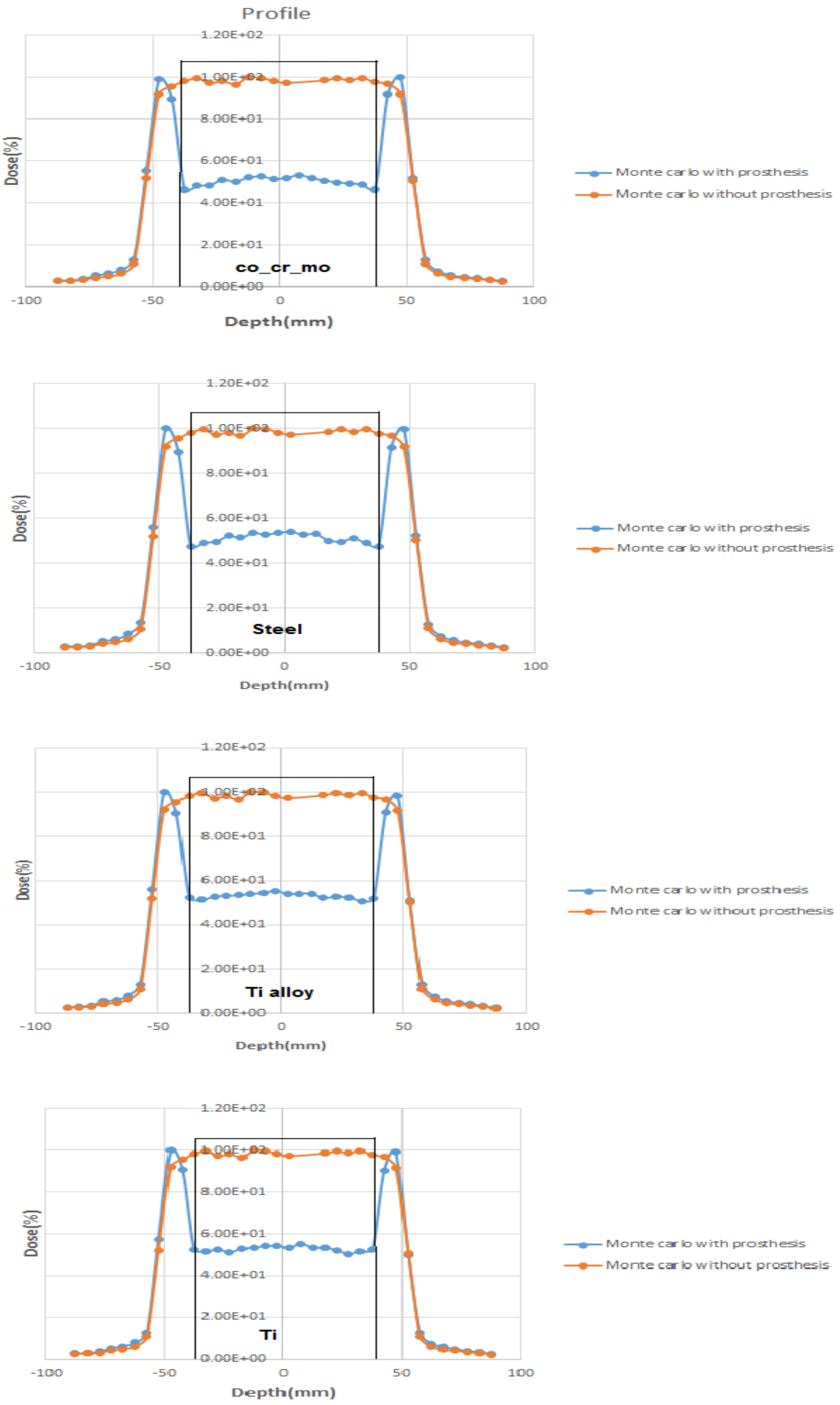

Figure 6: Dose profiles curves calculated by MC simulation with and without men's knee prostheses made of (a) chromium - cobalt – molybdenum alloy (b), stainless steel (c) titanium alloy and (d) titanium.

Table 2: Percentage of dose increment and reduction for different men and women prosthesis.

Material	Percentage of dose increment (%)		Percentage of dose reduction (%)	
	Men	Women	Men	Women
Cr _Co _ Mo alloy	6.81	6.4	41.18	40.87
SST	6.1	5.96	40.66	40.36
Ti alloy	4	3.87	37.76	36.94
Ti	4.29	3.94	37.51	36.69

est dose difference in the profile curve and titanium alloys had the lowest impact on dose distribution [23].

This study investigated the impacts of knee prosthesis on radiotherapy dose distribution. The results indicate that those areas completely blocked by the metal prosthesis experience a decrease in dose. Furthermore, the scattering effect of the beam from the metal leads to an increase in dose in knee bone and adjacent tissues. By changing the prosthesis material from high to low density, dose distribution and dose at the beginning and end of the metal decreased.

Conclusion

The metal prostheses in the radiation field leads to dose fluctuations in the tumor and normal tissue adjacent to the prosthesis. It can be assumed that changes dose depends on the material (density and atomic number) and the prosthesis cross-section. If the prosthesis cross-section and density increase, dose fluctuations in the surrounding area will ncrease which ultimately leads to a dose reduction in the tumor area and an increase in healthy tissues. Based on the results obtained, usage of titanium and titanium alloy with low density is recommended for knee joint arthroplasty. Also, more attention should be given to calculation related to the existence of prosthesis considering patients treatment time. While treatment planning of patients, undergone prosthesis implantation, it is recommended to emit the beam in such a way that the prosthesis is notin the path of radiation.

Acknowledgment

This work was supported by Arak University of Medical Sciences [Grant number: 1921].

Conflict of Interest

None

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