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Investigation of the Effects of Biomaterials Used in Cranioplasty on Radiotherapy Dose Through the Monte Carlo Method

Kranioplastide Kullanılan Biyomalzemelerin Radyoterapi Dozuna Etkisinin Monte Carlo Yöntemiyle Araştırılması

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Abstract

Aim: The gold standard in the treatment of brain tumors is radiotherapy and chemotherapy after surgery. Radiotherapy with high-energy ionizing radiation after surgery has an important place in the treatment of brain tumors. Implants with a high atomic number exhibit strong radiation attenuation and scattering properties that could potentially compromise the delivery of radiation therapy by distorting the dose distribution in and around the implant volume, complicating treatment planning in radiotherapy. In this study, it was aimed to investigate the interaction of biomaterials used in cranioplasty applications with X-rays used in radiotherapy using a GAMOS simulation.

Methods: The head phantom defined in the GAMOS simulation includes, from left to right, 0.2 cm of skin, 0.3 cm of soft tissue, 1 cm of skull, 12 cm of brain, 1 cm of skull, 0.3 cm of soft tissue, and finally, 0.2 cm of skin. In order to observe the effect of different biomaterials, selected biomaterials (CCM alloy, stainless steel, alumina, NiTi alloy, titanium, PEEK, PMMA, and PTFE) were defined instead of a 1 cm skull. In this configuration, the brain tissue is also defined as the detector to absorb energy.

Results: Cortical bone has a density of 1.920 g/cm^3 and the dose taken by the brain tissue was found to be 4,843 Gy. It was observed that the dose value absorbed in the brain tissue decreased with the increase in the densities of the biomaterials used in cranioplasty. Dose results for PTFE and PEEK biomaterials were found to be close to bone tissue.

Conclusion: As a result, PEEK and PMMA biomaterials, whose densities are very close to those of bone tissue, showed similarity to bone tissue in terms of radiotherapy dose distribution.

Keywords: biomaterials, cranioplasty, radiotherapy, GAMOS

Öz

Amaç: Beyin tümörlerinin tedavisinde altın standart cerrahi sonrası radyoterapi ve kemoterapidir. Cerrahi sonrası yüksek enerjili iyonlaştırıcı radyasyon ile radyoterapi beyin tümörlerinin tedavisinde önemli bir yere sahiptir. Yüksek atom numarasına sahip implantlar, implant hacmi içindeki ve etrafındaki doz dağılımını bozarak radyoterapide tedavi planlamasını zorlaştırarak radyasyon tedavisinin verilmesini potansiyel olarak tehlikeye atabilecek güçlü radyasyon zayıflaması ve saçılma özellikleri sergiler. Bu çalışmada, kranioplasti uygulamalarında kullanılan biyomalzemelerin radyoterapide kullanılan X-ışınları ile etkileşiminin bir GAMOS simülasyonu kullanılarak araştırılması amaçlanmıştır.

Yöntem: GAMOS simülasyonunda tanımlanan kafa fantomu, soldan sağa doğru 0,2 cm deri, 0,3 cm yumuşak doku, 1 cm kafatası, 12 cm beyin, 1 cm kafatası, 0,3 cm yumuşak doku ve son olarak, 0,2 cm cilt. Farklı biyomalzemelerin etkisini gözlemleyebilmek için 1 cm kafatası yerine seçilen biyomalzemeler (CCM alaşımı, paslanmaz çelik, alümina, NiTi alaşımı, titanyum, PEEK, PMMA ve PTFE) tanımlandı. Bu konfigürasyonda, beyin dokusu aynı zamanda enerjiyi emen detektör olarak tanımlanır.

Bulgular: Kortikal kemiğin yoğunluğu 1.920 g/cm^3 olup, beyin dokusunun aldığı doz 4.843 Gy olarak bulundu. Kranioplastide kullanılan biyomateryallerin yoğunluklarının artması ile beyin dokusunda soğurulan doz değerinin düştüğü gözlendi. PTFE ve PEEK biyomateryalleri için doz sonuçlarının kemik dokusuna yakın olduğu bulundu.

Sonuç: Sonuç olarak yoğunlukları kemik dokusuna çok yakın olan PEEK ve PMMA biyomateryalleri radyoterapi doz dağılımı açısından kemik dokusuna benzerlik göstermiştir.

Anahtar Kelimeler: biyomalzemeler, kranioplasti, radyoterapi, GAMOS

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Introduction

Approximately 1-2% of all malignancies are caused by central nervous system (CNS) tumors (1). Although they are rarely seen, they have high morbidity and mortality rates (2). Especially in high-grade tumors such as anaplastic astrocytoma and glioblastoma, the five-year survival rate varies between 5.5 and 29.7% (3,4). Radiotherapy and chemotherapy are considered the prevailing treatment modalities for brain tumors subsequent to surgical intervention, establishing the gold standard in clinical practice (5). Craniectomy is a common procedure that may be needed for tumor infiltration of the skull bone and a malignant middle cerebral artery infarction (6). The term "cranioplasty" refers to a surgical procedure aimed at restoring the integrity and functionality of the skull by repairing any cranial defects (7). The ideal cranioplasty material should have good biocompatibility, compatibility with imaging, skull contour reconstruction, cerebral protection, osteogenic potential, and avoidance of donor site problems. Different biomaterials (titanium, stainless steel, PEEK, PTFE, etc.) are used in cranioplasty applications. The utilization of high-energy ionizing radiation in the form of radiotherapy following surgical intervention holds significant significance in the management of brain tumors. Today, different treatment techniques are used with the developing technology to reduce radiotherapy's side effects and obtain a homogeneous dose distribution. Two of these techniques are intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) (8). However, the utilization of prosthetic devices in various applications, such as cranioplasty, gives rise to nuclear interactions with high-energy ionizing radiation, hence leading to the generation of secondary particles. Implants with high atomic numbers possess notable characteristics in terms of radiation attenuation and scattering. These features have the ability to hinder the effective administration of radiation therapy by causing distortions in the distribution of radiation doses within and surrounding the implanted area. Consequently, this complicates the process of treatment planning in the field of radiotherapy (9). Although there are techniques such as IMRT and VMAT designed to prevent uncertainty that must be defined mathematically arising from these implants, the treatment could not be optimized as necessary due to the reduction of possible beams passing through the implant, the reduction of degrees of freedom, and potentially the limitation of dosimetric quality (10,11).

The objective of this work was to examine the interaction between biomaterials used in cranioplasty procedures and X-rays employed in radiotherapy, employing a Monte Carlo simulation. The results obtained from eight different biomaterials used in the study were compared with those obtained for the skull, known as cortical bone. They showed which biomaterial was similar to bone in terms of the interaction of X-rays.

Method

2.1. Monte Carlo Simulation

Numerous Monte Carlo programs have been effectively employed in the realm of radiation simulations (12,13). The four most widely utilized software packages in the field are BEAMnrc (14), MCNP (15), PENELOPE (16), and GEANT4 (17). These scripts employ specific programming languages, such as C++, which may provide challenges for researchers who lack familiarity with these programming languages. In contrast, there exist software applications that serve as intermediaries between users and the aforementioned primary programs. These secondary software applications use the underlying code of the main product, hence eliminating the requirement for the user to acquire any expertise in programming languages. One example of such software is GAMOS. The GAMOS software framework, which is extensively employed in the field of medical physics, is built around the GEANT4 toolkit (18). The simulations in this study were conducted using the GAMOS v.6.2.0 software program.

The geometry file was defined for GAMOS simulation. Gun and target volumes were created in the center of the Linac banker, which consists of 2000x2000x2000 cm^3 air. The tungsten collimator was defined in the banker, and the collimator field size was determined to be 5x5 cm^2. In radiotherapy, slab, cylindrical, and Alderson phantoms are used to plan the treatment of different parts of the human body. This study defined the source skin distance as 100 cm in the slab

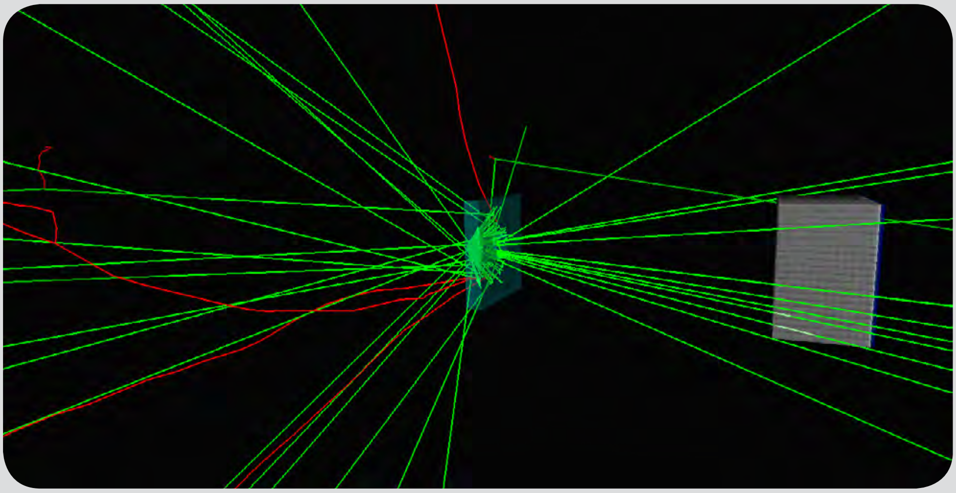

Figure 1. Geometry of GAMOS simulation.

phantom geometry file. The phantom comprises layers arranged from left to right, consisting of 0.2 cm of skin, 0.3 cm of soft tissue, 1 cm of skull, 12 cm of brain, 1 cm of skull, 0.3 cm of soft tissue, and 0.2 cm of skin. The chosen biomaterials were individually substituted for the 1 cm cranium to investigate the impact of various biomaterials. In the present arrangement, brain tissue is also designated as the energy absorption medium (Figure 1).

The input file encompassed the definition of parameters related to physics, generator, and dose collecting. The electromagnetic physics package was employed in the simulation. The simulations were conducted with a gamma ray energy of 6 MeV. The scoring criteria involved quantifying the dose detected by the mechanisms of "GmG4PSDoseDeposit". The input file did not utilize any filter or user action command. All particles that arrived at the detector were included in the analysis. While the scoring system incorporated all physical processes, vari-

Table 1. Densities of biomaterials and dose estimates were obtained from a GAMOS simulation.

Material	Density (g/cm^3)	Dose (Gy)	Difference (%)
Bone	1,920	4,843	-
Alumina	3,900	4,796	0,981
CCM Alloy	2,670	4,806	0,760
NiTi Alloy	6,700	4,712	2,781
PEEK	1,320	4,844	0,030
PMMA	1,200	4,847	0,082
PTFE	2,200	4,838	0,094
Ti-6Al-4V	4,430	4,754	1,862
Stainless Steel	8,030	4,659	3,951

ance reduction strategies were not employed. A dataset consisting of 10^7 photons was employed to enhance the accuracy of the Monte Carlo simulations and minimize statistical uncertainty.

$$Difference\ (\%) = \left|\frac{D_{Bone} - D_{Biomaterial}}{D_{Bone}}\right| x100$$

Equation 1 was used to find the percentage difference between the dose values for bone and biomaterials from the GAMOS simulation study.

2.2. Use Of Biomaterials In Cranioplasty

There are many different biomaterials preferred for cranioplasty. Stainless steel is a metal material commonly used to reconstruct hard tissues such as bone. Stainless steel has quickly become suitable for neurosurgeons due to its low cost and good machinability (19). Polyetheretherketone (PEEK), a material widely recognized and extensively employed in the field of spine surgery, has recently found application in the domain of cranioplasty (20-24). Polymethylmethacrylate (PMMA) is a self-curing acrylic resin that can be used to repair cranial defects (25). CCM alloy, also referred to as vitallium, is an alloy composed of cobalt, chromium, and molybdenum. It is utilized for the purpose of repairing cranial abnormalities (26). Alumina has been widely utilized as the preferred bioceramic material for dental implants and cranioplasty procedures for an approximate duration of three decades (27). Polytetrafluoroethylene (PTFE), a polymeric biomaterial), It is used in many areas, such as cranioplasty (28). Titanium alloy (Ti, Al, V) and NiTi alloy have been adopted as prostheses in orthopedic applications (29,30).

Results

The densities of the implant materials used in the study and the dose amounts in the brain tissue are given in Table 1. Cortical bone has a density of 1.920 g/cm^{3,} and the dose taken by the brain tissue was found to be 4,843 Gy. It was observed that the dose value absorbed in the brain tissue decreased with the increase in the densities of the biomaterials used in cranioplasty. Dose results for PMMA and PEEK biomaterials were found to be close to bone tissue.

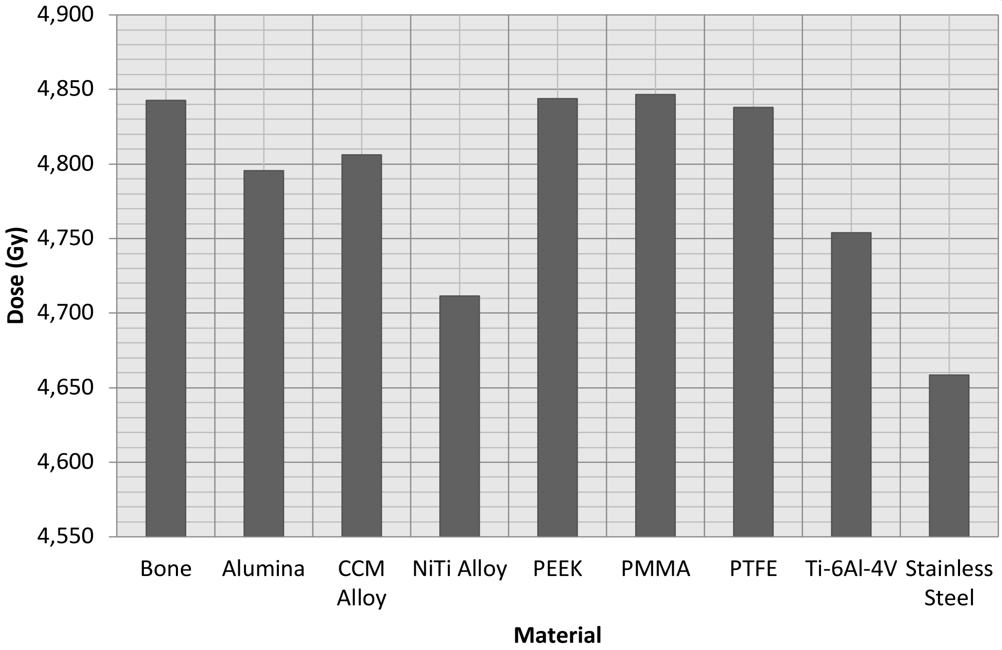

Figure 2. Dose value for different implant materials.

The dose values of stainless steel and Ti-6Al-4V alloys showed a significant decrease compared to bone tissue (Figure 2).

Discussion

This study investigated the effect of different biomaterials used in cranioplasty surgery on the radiotherapy dose. The obtained findings were compared with bone tissue.

In a study using titanium and steel spinal implants, the dosimetric perturbation effect of these implants at different photon energies was investigated (31). Calculations using the MCNP4C Monte Carlo code showed a dose reduction of 5.0 – 6.2 % and 10.2 – 11.2 %, respectively, in the doses they received after the titanium and steel rods (31).

In an adult male head and neck phantom, measurements were taken between the mandible and soft tissue with TLD while the titanium alloy plate and screws were mounted or not, and the effect of the implant on the radiation dose was examined. As a result of measurements with and without implants, dose differences ranging from 2.1 to 3.0% were observed (32).

In another study, hip implants produced from stainless steel, titanium, and cobalt chrome molybdemium (Co-Cr-Mo) using Monte Carlo simulation, beam profiles were measured at a depth of 20 cm in a modeled water phantom. They reported a 25-45% dose reduction for stainless steel and 20-25% for titanium (33).

5. Conclusion

Several biomaterials have been investigated as alternatives to cortical bone, including PMMA, PEEK, PTFE, CCM Alloy, Alumina ceramic alloy, and titanium alloys. These materials have shown promising results in closely resembling the properties of natural bone. The primary factor contributing to this phenomenon is the similarity in density between the biomaterial utilized and the cortical bone. Based on the findings presented, evaluating the specific type of biomaterial used in cranioplasty surgery is imperative when determining the optimal dosage for radiotherapy.

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