Dose distribution close to metal implants in Gamma Knife Radiosurgery: A Monte Carlo study

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Materials with high atomic numbers favor the occurrence of the photoelectric effect when they are irradiated with gamma rays. Therefore, the photoelectric effects of metal implants within the target regions in Gamma Knife Radiosurgery are worth studying. In the present work, Monte Carlo simulations using EGS4 were employed to investigate the resulting dose enhancements. A dose enhancement as high as 10% was observed close to a platinum implant along the x and y axes, while no significant dose enhancements were observed for silver, stainless steel 301, and titanium ones. A dose enhancement as high as 20% was observed close to the platinum implant along the z axis at the superior position of the metal–phantom interface and was 10% higher for other metal implants. [DOI: 10.1118/1.1582811]

Key words: Leksell Gamma Knife, GammaPlan, EGS4 Monte Carlo, metal implants

I. INTRODUCTION

Foreign objects are sometimes implanted in a human brain due to certain neurological conditions such as cerebral aneurysm. When Gamma Knife Radiosurgery has to be performed in those patients with metal implants at the treatment target, the dose distribution cannot be predicted correctly by the present treatment planning system, GammaPlan,[1] because the calculations performed by the GammaPlan are based on a homogeneous water equilibrium phantom.

Cerebral aneurysms are balloonlike sacs formed in weakened areas of arteries, which bring blood to the brain, and can rupture. Intracranial bleeding can cause neurological deficits or even immediate death. The first aneurysm clip was employed by Walter Dandy on 23 March 1937,[2] and malleable silver was used. Over the years, the design and material were improved to prevent slippage. By 1952, Mayfield and colleagues chose stainless steel 301, believing that it was malleable while retaining adequate spring recoil.[3] Since MR imaging was introduced, the first titanium clip was devised.[4] Nowadays, most aneurysm clips are made of titanium. A sketch of a common titanium aneurysm clip is shown in Fig. 1.

Aneurysm clipping requires a craniotomy which may not be favorable to elderly patients or those in poor medical conditions. The Guglielme Detachable Coil (GDC) system was used to localize and obliterate the aneurysm.[5] Soft platinum coils were deployed into the aneurysm under fluoroscopy.

In this study, the Monte Carlo technique using EGS4 was employed to calculate the dose distributions for Gamma Knife surgery regarding various kinds of foreign metal materials, such as silver, stainless steel 301, titanium, and platinum. Details of implementation of Monte Carlo technique on Leksell Gamma Knife can also be found in our previous publications.[6–8]

II. METHODOLOGY

The Monte Carlo system employed is the PRESTA (Parameter Reduced Electron-Step Transport Algorithm) version of the EGS4 (Electron Gamma Shower) computer code. Detailed descriptions of the structure of the EGS4 code can be found in Ref. 9. In the simulation, the patient's head was modeled by a spherical water phantom 160 mm in diameter. Each one of the 201 sources located in the Gamma Knife radiation unit consists of 20 cylindrical ^{60}Co pellets 1 mm in diameter and 1 mm in length. Each source was therefore modeled by a cylinder 1 mm in diameter and 20 mm in length. To simplify the simulation geometry, surgical clips or coils were modeled by a 2 mm radius sphere at the center of the water phantom. The radius of 2 mm was chosen to be comparable to the size of the aneurysm clip/coil. Furthermore, the 2 mm radius sphere was large enough to give a good resolution in the simulation. The materials of the studied metal objects were silver, stainless steel 301, titanium, and platinum. Table I shows the detailed information of these materials.

The ^{60}Co sources are arranged in a sector of a hemispherical surface with a radius of about 400 mm, and are distributed along five parallel circles separated from each other by an angle of 7.5°.[10] The 201 radiation beams pass through the opening of the collimators to reach the target point. The diameters of the radiation beams at the focus are confined by the collimators. In this study, the 14 mm collimator helmet

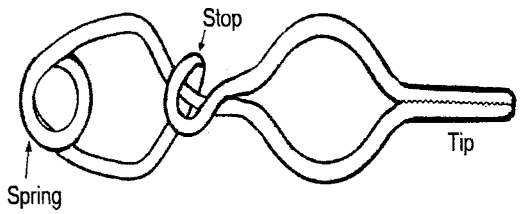

FIG. 1. Sketch of a common titanium aneurysm clip.

TABLE I. Properties of the studied foreign metal materials. Compositions of Steel 301 are taken from Ref. 12.

	Atomic No.	Compositions	Density
Silver	47	Ag 100%	10.5
Platinum	78	Pt 100%	21.45
Steel 301	n.a.	C 0.15%, Mn 2.0%, P 0.045%, S 0.03%, Si 0.75%, Cr 18.0%, Ni 8.0%, N 0.1%. Fe 70.925%	7.88
Titanium	22	Ti 100%	4.54

was employed. Single shots with all 201 gamma beams opened were delivered at the center (unit center point: $x = 100$ mm, $y = 100$ mm, $z = 100$ mm) of the water phantom. Scoring bins with dimensions $0.5\times 0.5\times 0.5\ \mathrm{mm}^3$ were set up along the three main principal axes. The absorbed dose values were obtained by dividing the energy depositions in the scoring bins by their masses.

A total of 2.5×10^8 histories were obtained in the simulations. The history runs were divided into 50 batches for calculation of statistics. The standard errors for all calculations were less than 1.2%. The simulation duration for 10^4 history runs took 27 s in a Windows 2000® based Pentium III 733 PC with a PowerStation 4.0 Fortran compiler. The photon spectrum of ^{60}Co contained two peaks, viz. 1.173 and 1.333 MeV. The cutoff energies for electrons and photons were set to be 0.521 and 0.01 MeV, respectively. A long sequence random number generator[11] was employed. This has a sequence length of about 10^{43}, effectively infinite for our calculations, and has about 10^9 independent sequences that can be selected from initial conditions.

III. RESULTS

First, the EGS4 user code was used to generate dose distribution curves along the three principal axes using the 14 mm collimator helmet when a single shot was delivered at the unit center point (100, 100, 100) of the homogeneous water phantom, and the results were compared with those calculated by GammaPlan. They were found to be in perfect agreement, with discrepancies smaller than 2%. After the user code was verified, spheres of different metal materials and with a radius of 2 mm were introduced in turn at the center of the phantom. Figure 2 shows the variation of the relative doses along the x-axis with and without the presence of the metal objects. A dose enhancement as high as 10% was observed close to the platinum object. The dose en-

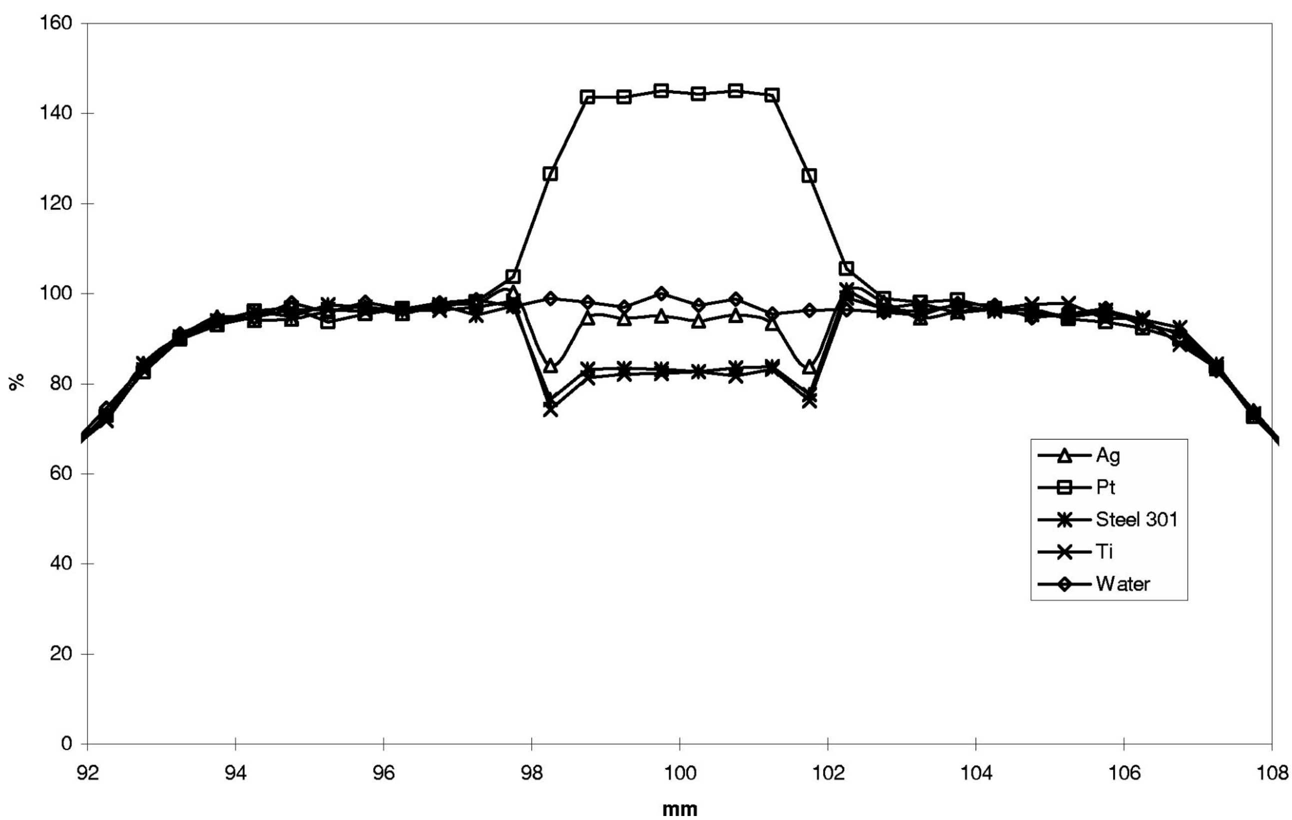

FIG. 2. Comparison of the relative doses along the x axis with and without the presence of metal objects (silver, stainless steel 301, titanium, and platinum).

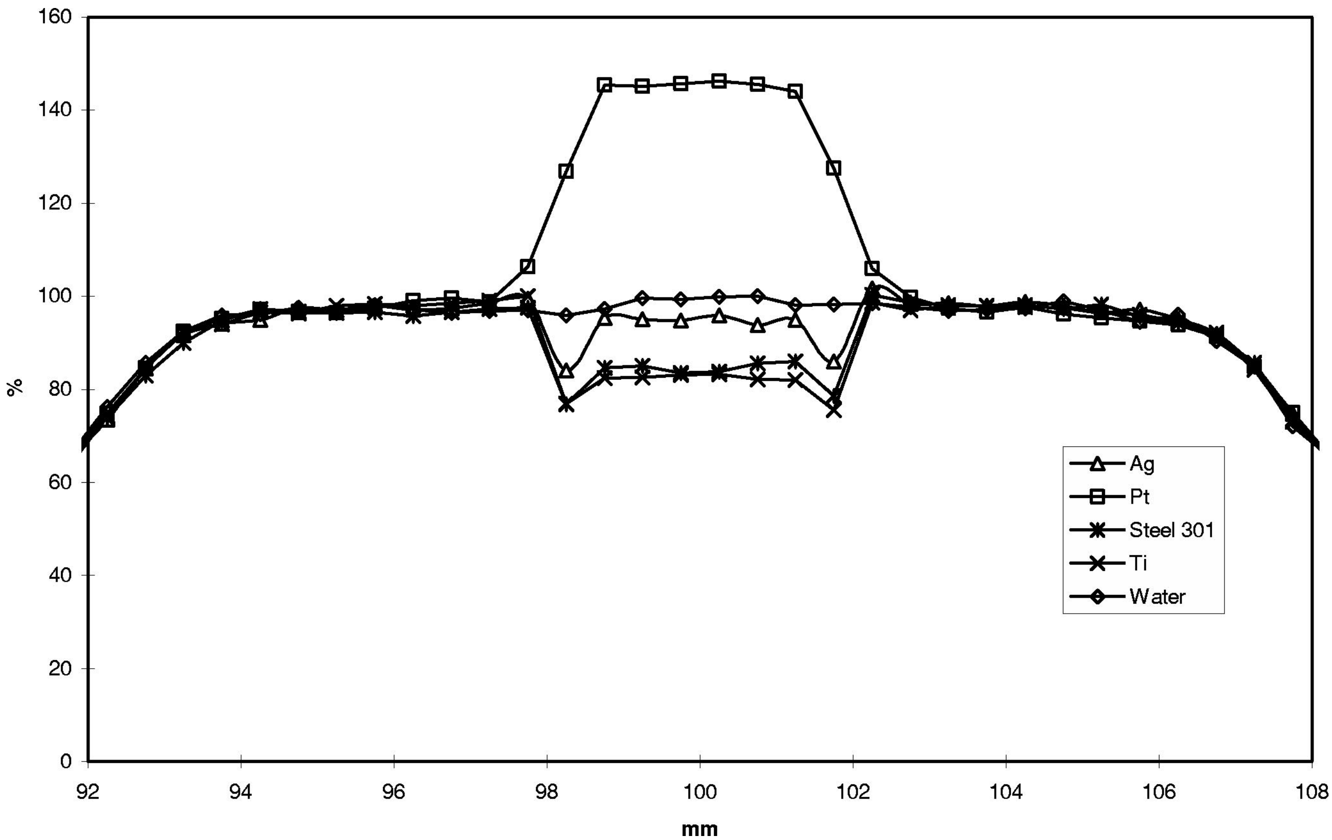

FIG. 3. Comparison of the relative doses along the *y* axis with and without the presence of metal objects (silver, stainless steel type-301, titanium, and platinum).

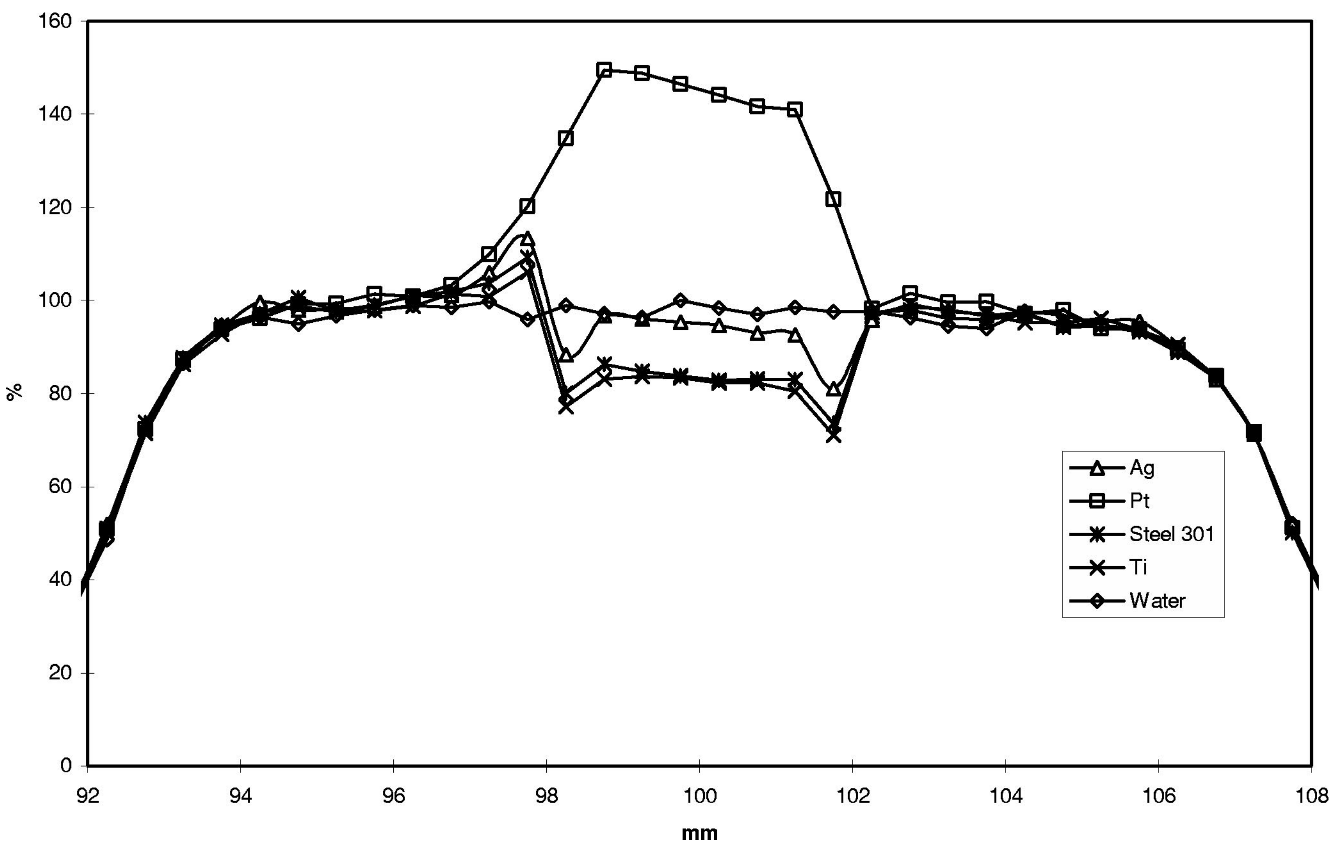

FIG. 4. Comparison of the relative doses along the *z* axis with and without the presence of metal objects (silver, stainless steel type-301, titanium, and platinum).

hancement is due to the generation of secondary electrons from photoelectric effect. In this case, interactions were made with platinum which has a large atomic number and thus has a large total cross-section for photoelectric effect. For other metal objects, an underdose was observed because of the dominance of photon attenuation over photoelectric effect. A small dose build-up at the center was due to the decrease of photon energy along its path and this decrease in photon energy further enhances the photoelectric effect. Due to the symmetry of the Gamma Knife collimator helmet, the explanations for the patterns in Fig. 3 are the same as those for the patterns in Fig. 2. For Fig. 4, the explanations were also similar but the dose enhancement was observed at the superior position of the metal–phantom interface for all metal objects. The dose enhancement was 20% higher when close to the platinum object and 10% higher when close to other metal objects. There were no direct gamma beams coming along the z-axis and therefore small dose enhancements could be easily observed along the z-axis at the superior position of the metal-phantom interface.

IV. CONCLUSIONS

Dose enhancements were observed in Gamma Knife Radiosurgery when metal implants, such as aneurysm clips and Guglielme detachable coils (GDC), were within the target regions. The effect was significant for platinum objects which had a high atomic number and therefore favored the occurrence of the photoelectric effect. Particular care should be taken in Gamma Knife Radiosurgery when irradiating platinum objects, such as platinum made GDC, when they are close to vital brain structures. For other metal objects such as silver, stainless steel 301, and titanium, dose enhancements due to photoelectric effect can only be observed at the superior position of the metal–phantom interface.

The treatment planning system GammaPlan can only reproduce the Monte Carlo results at radial distances far away from the metal implants, because the algorithm of the GammaPlan focuses only on the homogeneous phantom. The Monte Carlo results of the dose distribution close to the metal implants in Gamma Knife Radiosurgery are difficult to obtain through measurements. The calculated enhanced doses due to secondary electrons exiting from the metal implants can serve as a reference for Gamma Knife centers around the world.

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