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Dosimetric perturbations due to an implanted cardiac pacemaker in balloon breast brachytherapy

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Abstract

Dosimetric perturbations due to an implanted cardiac pacemaker in balloon breast brachytherapy

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Purpose: To investigate dose perturbations for pacemaker-implanted patients in partial breast irradiation using high dose rate (HDR) balloon brachytherapy.

Methods: Monte Carlo (MC) simulations were performed to calculate dose distributions involving a pacemaker in Ir-192 HDR balloon brachytherapy. Dose perturbations by varying balloon-to pacemaker distances (BPD = 50 or 100 mm) and concentrations of iodine contrast medium (2.5%, 5.0%, 7.5%, and 10.0% by volume) in the balloon were investigated for separate parts of the pacemaker (i.e., battery and substrate). Relative measurements using an ion-chamber were also performed to confirm MC results.

Results: The MC and measured results in homogeneous media without a pacemaker agreed with published data within 2% from the balloon surface to 100 mm BPD. Further their dose distributions with a pacemaker were in a comparable agreement. The MC results showed that doses over the battery were increased by a factor of 3, compared to doses without a pacemaker. However, there was no significant dose perturbation in the middle of substrate but up to 70% dose increase in the substrate interface with the titanium capsule. The attenuation by iodine contrast medium lessened doses delivered to the pacemaker by up to 9%. The volume of lung increases the dose to a pacemaker (DPF: 1.1~1.3) while the volume of bone decreases the dose to a pacemaker (DPF: 0.8~0.9).

Conclusions: Due to inhomogeneity of pacemaker and contrast medium as well as low-energy photons in Ir-192 HDR balloon brachytherapy, the actual dose received in a pacemaker is different from the homogeneous medium-based dose and the external beam-based dose. Therefore, the dose perturbations should be considered for pacemaker-implanted patients when evaluating a safe clinical distance between the balloon and pacemaker. BPD = 100 mm and 200 mm were estimated for safety of substrate and battery respectively.

Key Words: implanted cardiac pacemaker, balloon breast brachytherapy,

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Introduction

The recent increase in cardiovascular ailments has resulted in a growing population of patients with an in situ cardiac pacemaker.[1] Pacemaker patients under radiation treatments are exposed to a potential risk of pacemaker malfunctions. It was reported that there might be two malfunction mechanisms.[2] First of all, a klystron or magnetron in linear accelerators produces electromagnetic interference, disturbing cardiac signal recognition in a pacemaker. Secondly, ionizing radiation causes direct damage to the complementary metal oxide semiconductor (CMOS) circuitry inside a pacemaker. Regarding the second malfunction, the direct damaging mechanism is still unknown, but for patient safety the tolerance dose of 2 Gy to a pacemaker has been established as a recommendation.[2-4] In the United States annually 230,480 new cases of breast cancer patients are potential radiation treatment candidates with an implanted pacemaker.[5] Due to the proximity between an implanted pacemaker and the treatment site of breast cancer, the radiation-induced malfunction had been reported.[6, 7] Recently, treatment planning guides for patients treated with external beams were suggested.[8-10]

An applicator including a balloon and catheter called MammoSite® (Hologic Inc, Bedford, MA) was developed for accelerated partial-breast irradiation (APBI) using a high dose rate (HDR) Ir-192 source. In general, the prescription dose is 34 Gy in 10 fractions delivered twice daily at least 6 hours apart over 5 consecutive working days.[11] However, radiation issue regarding pacemaker-implanted patients has not been well addressed yet. Recently, Kim et al[12] estimated the amount of dose deposited to a pacemaker based on retrospective clinical data. But, those data were calculated by the commercial treatment planning system (TPS), BrachyVision V8.9 (Varian Medical Systems, Inc., Palo Alto, CA) that did not account for inhomogeneity often encountered in HDR balloon brachytherapy.[13] In the balloon brachytherapy, the radiation from a Ir-192 source includes a large portion of low-energy spectrum, which is primarily subject to photoelectric effect with high-Z elements of contrast medium. Likewise, it was pointed out that the homogeneous medium assumption in brachytherapy planning systems causes dose discrepancy.[13-19] Recently, an advanced algorithm such as BrachyVision Acuros (Varian Medical Systems, Inc. Palo Alto, CA) has been released to account for the tissue inhomogeneity. However, it is still challenging to calculate doses involving a pacemaker that is subject to extended Hounsfield units (HU) in commercial planning systems.

In this study, we carried out Monte Carlo (MC) simulations to estimate dose perturbations due to the pacemaker in HDR balloon brachytherapy. We assumed two different balloon-to-pacemaker distances (BPD) and four different concentrations of contrast medium in the balloon. With a special interest, separate dose distributions through the battery and substrate of pacemaker were investigated. In addition to MC, in-water measurements using an ion-chamber (IC) were performed in cases of with and without a pacemaker.

Materials and Methods

1. Measurement

Dose readings with and without a pacemaker for a single dwell position were measured in 10 mm intervals along the transverse plane of the source from the closest accessible point out to a distance of 150 mm. As shown in Figure 1 and Figure 2, a 0.125 cc ion-chamber (Model 31010, PTW, Hicksville, NY) was mounted to a detector holder in the scanning water tank (Scanditronix Wellhofer Blue Phantom 2, IBA Dosimetry, Bartlett, TN, USA). In the water tank, a MammoSite® balloon was injected with 30 cc water to maintain a diameter of 40 mm throughout the measurements. The balloon was held stationary with a foam box inside the water tank so that the catheter was parallel to the tank wall. The MammoSite® applicator was always placed in the vertical direction in order to keep the connector between the catheter and the transfer guide tube out of the water. A pacemaker (Model KD903 KAPPA, Medtronic, Vitatron, Guidant and St Jude Medical) was taped to the top of the water-equivalent solid phantom. The bottom of the solid phantom was attached to a lead block in the water tank to maintain its stationary position in the water. The assumption was made that there is little influence of the lead block and was therefore ignored. The pacemaker attached to the solid phantom was placed at 50 mm and 100 mm respectively from the balloon surface. The measurements were performed using the Ir-192 HDR remote afterloader system (Nucletron Corp., Veenendaal, Netherlands).

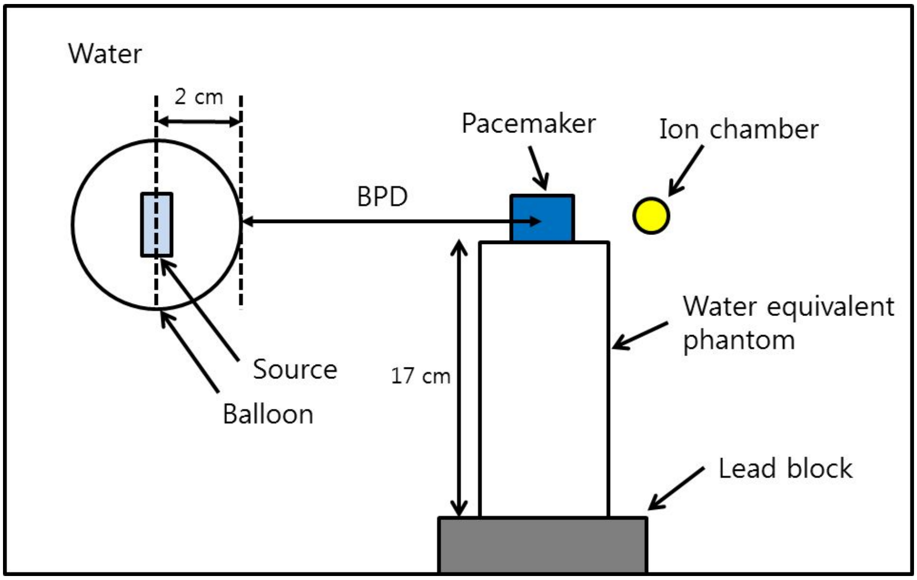

FIG. 1. A schematic diagram of the measurement setup including a pacemaker on water equivalent phantom and an ion-chamber for a given BPD. Plot is not in scale

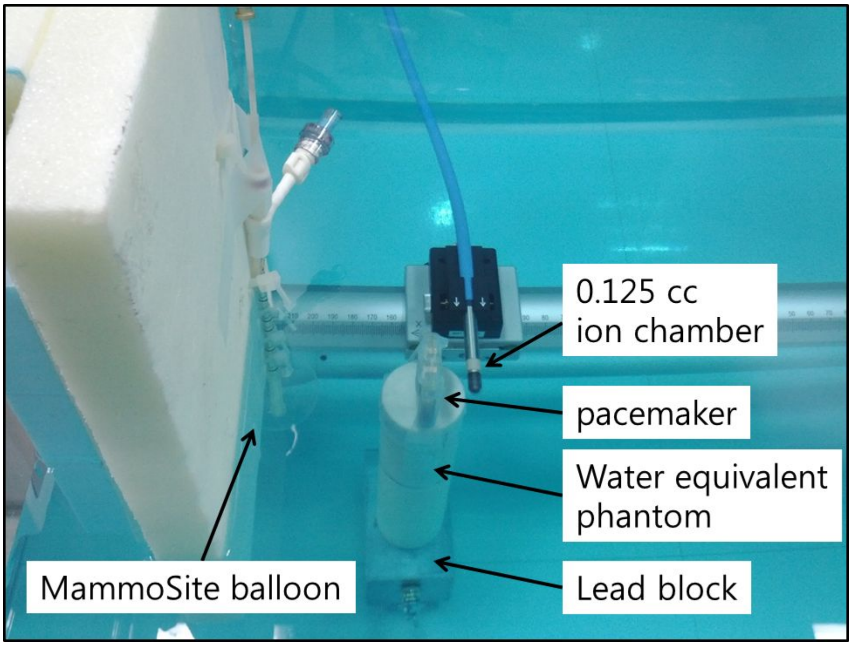

FIG. 2. Photographs showing the measurement setup

All measurements were completed within a short period of time (~ 2 hours) so that the decay of source activity during the measurement was negligible. The major potential error was due to the uncertainty of detector positioning. To validate the positioning accuracy, we compared IC measurements with published data[20] and repeated the same measurements using a small diode detector (Edge Detector, Sun Nuclear Corp., Melbourne, FL) before placing a pacemaker. Since the outer diameter of source is 0.9 mm and the inner diameter of catheter is 2.0 mm, the maximum deviation between the centers of source and catheter was ±0.55 mm. The inherent positioning accuracy and reproducibility of the scanning water tank system was ±0.1 mm [Blue Phantom 2 User's Guide PW-04-002-510-003 (IBA Dosimetry GmbH, Germany)]. Therefore, the maximum error of positioning is ±0.65 mm, which gives the maximum dose error estimation of ±1% at BPD=50 mm and ±0.6% at BPD=100 mm. The assumption was made that the displacement effect for the cylindrical ion-chamber was not of concern because the inverse square law is dominant at small source-to-detector distances in this setup[21] and positioning error will lead to a large error.

2. Monte Carlo calculations

We performed Monte Carlo simulations using GEANT4.9.2p01[22] with GATE v6.0p01[23] platform. The GEANT4/GATE simulation platform was previously verified for low-energy brachytherapy calculations.[24] The cutoff energies used in the calculations were 5 keV for photon and 600 keV for electron. The theoretical photon spectra of Ir-192 were taken from Glasgow and Dillman.[25] No variance reduction techniques were used. The dose was scored by the *DoseActor* which is a GEANT4/GATE tool to collect dose information.[23] The size of voxel was $2.5 \times 2.5 \times 2.5$ mm^3. In this simulation, we used the electromagnetic low-energy physics model that explicitly considers all possible electron and photon interactions in low energy (photoelectric effect, Compton scattering, gamma conversion, Rayleigh scattering, bremsstrahlung, electron ionization, and multiple scattering). The accuracy of the cross-section libraries and the transport algorithms have been verified and described elsewhere.[24]

Figure 3 shows the schematic diagram of Ir-192 source and pacemaker for the Monte Carlo simulations. The Ir-192 source was simulated as a cylinder where the iridium wire was centered within the encapsulation. The iridium wire was a cylinder of 0.65 mm diameter and 3.6 mm length. The encapsulation was a 4.7 mm-long stainless steel tube having inner and outer diameters of 0.65 mm and 0.9 mm, respectively. A balloon of 40 mm diameter was embedded into the water tank. We assumed 0%, 2.5%, 5.0%, 7.5%, and 10.0% (by volume) concentrations of contrast medium in the balloon.[15] The BPD were 50 mm and 100 mm as in the measurement setup. In order to determine clinically safe distance, simulations were also performed in setup of BPD = 150 mm and 200 mm. Pacemaker modeling was simplified as shown in Figure 3. The inner part of pacemaker was divided into a silicon substrate and a battery composed of 60% iodine and 40% iron by weight. We used the composition data of Gossman et al[8] for the battery. A titanium box of 2 mm thickness enclosed the pacemaker inner components.

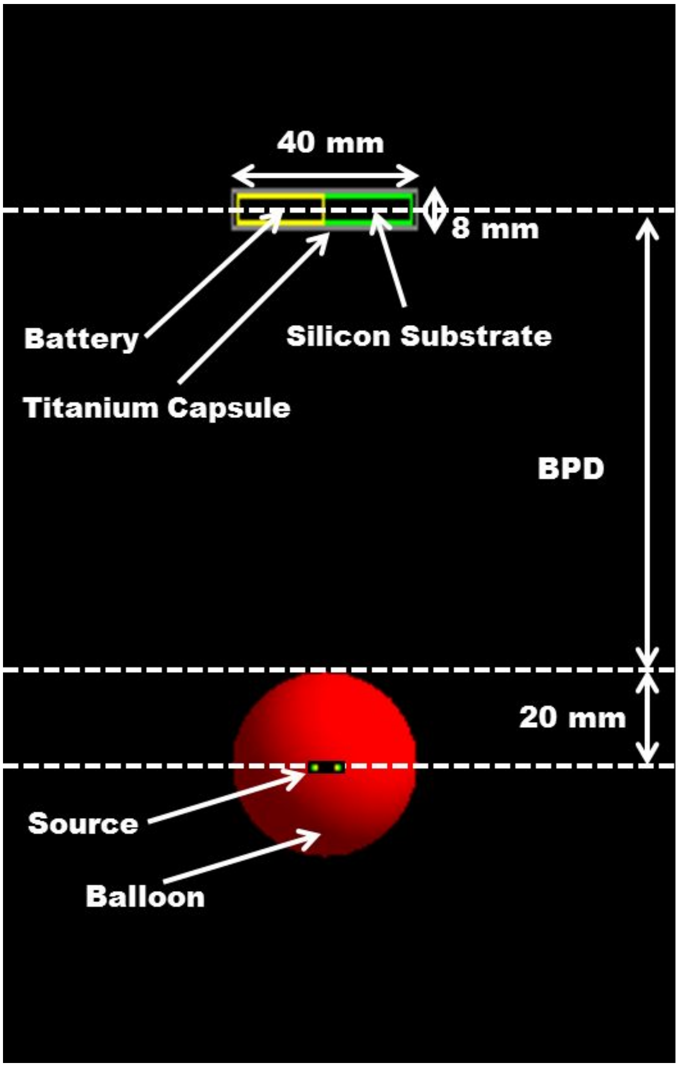

FIG. 3. A schematic diagram of the geometry used in GEANT4 Monte Carlo simulation

Figure 4 shows the schematic diagram for treatment involving lung and bone in the Monte Carlo simulations. Ir-192 and pacemaker modeling was same as described above. The simulations were only performed for BPD = 200 mm situations because it was determined as the minimum distance based on previous works. For lung-only situation, the lung was placed in the middle of balloon surface and a pacemaker. The length of lung was 50 mm. For lung and bone situation, the two bone tissues surround a lung tissue by each length of 10 mm.

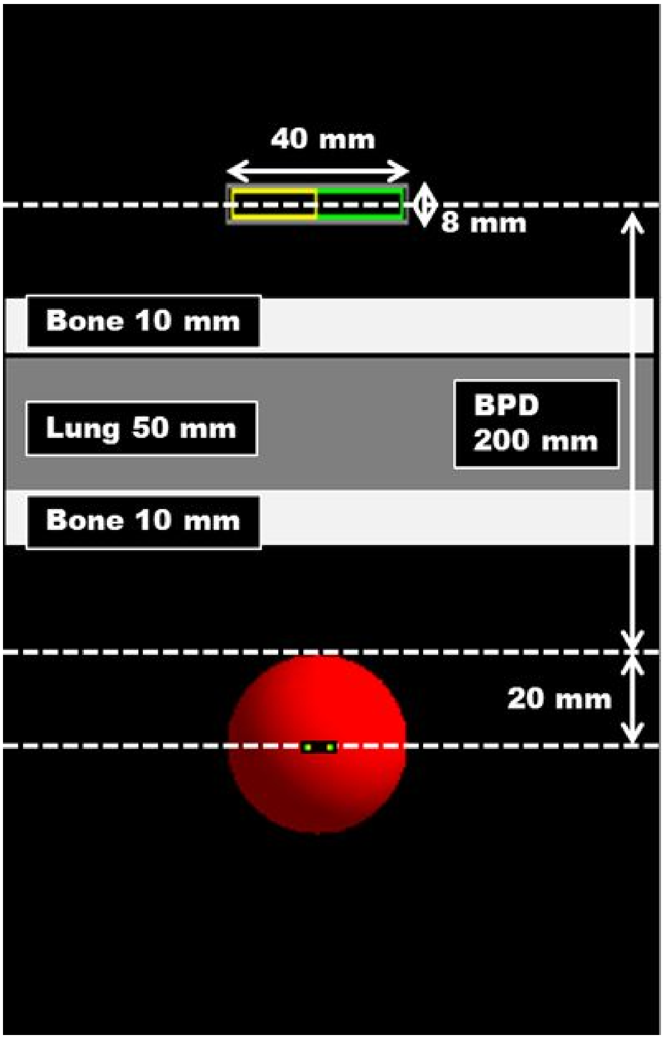

FIG. 4. A schematic diagram of the geometry in Monte Carlo simulation involving lung and bone

The atomic compositions and densities of the materials assumed in MC simulations are summarized in Table 1. Total histories of 2×10^9 primary photons from the source were simulated to generate voxel doses along the Cartesian coordinate (±x, ±y, and ±z) with statistical uncertainties less than 5%. But, statistical uncertainties at the pacemaker location for BPD of 50 mm and 100 mm were within 2% and 3%, respectively. In order to quantify the dosimetric effect of pacemaker, a dose perturbation factor (DPF), defined as the ratio of the dose with a pacemaker under various contrast conditions to the dose without a pacemaker under the no contrast condition, was introduced.

TABLE I. Elemental composition

Component	Material	Mass fraction	Density (g/cm3)
Active wire	Iridium	1.0 Ir	22.42
Encapsulation	Stainless steel	0.02 Si, 0.18 Cr, 0.02 Mg, 0.67 Fe, 0.11 Ni	8.02
Balloon 2.5%	Iohexol – Water mixture	0.0099 C, 0.1091 H, 0.0166 I, 0.0018 Ni, 0.8626 O	1.01
Balloon 5.0%	Iohexol – Water mixture	0.0191 C, 0.1064 H, 0.0320 I, 0.0035 Ni, 0.8390 O	1.02
Balloon 7.5%	Iohexol – Water mixture	0.0283 C, 0.1038 H, 0.0473 I, 0.0052 Ni, 0.8154 O	1.03
Balloon 10%	Iohexol – Water mixture	0.0375 C, 0.1012 H, 0.0626 I, 0.0069 Ni, 0.7918 O	1.04
Pacemaker case	Titanium	1.0 Ti	4.51
Substrate	Silicon	1.0 Si	2.33
Battery	Battery	0.6 I, 0.4 Fe	6.11
Lung	Mixture	0.103 H, 0.105 C, 0.031 Ni, 0.749 O, 0.002 Na, 0.002 P, 0.003 S, 0.003 Cl, 0.002 K	0.26
Bone	Mixture	0.034 H, 0.155 C, 0.042 Ni, 0.435 O, 0.001 Na, 0.002 Mg, 0.103 P, 0.003 S, 0.225 Ca	1.92

Results

1. Validation

To validate the robustness of our measurements and MC calculations, we compared both dose distributions with published data. Figure 5 shows the dose distributions without a pacemaker vs. distances from the balloon surface. The doses were normalized to the dose at 10 mm from the balloon surface, which is the prescription depth of balloon breast brachytherapy. The IC results were almost completely coincided with Daskalov et al data.[20] The MC calculations agreed well with Daskalov et al data to within 1% and with the IC results to within 2%. Also, the differences between the IC and diode measurements (EDGE) were less than 5% up to 100 mm distance from the balloon surface.

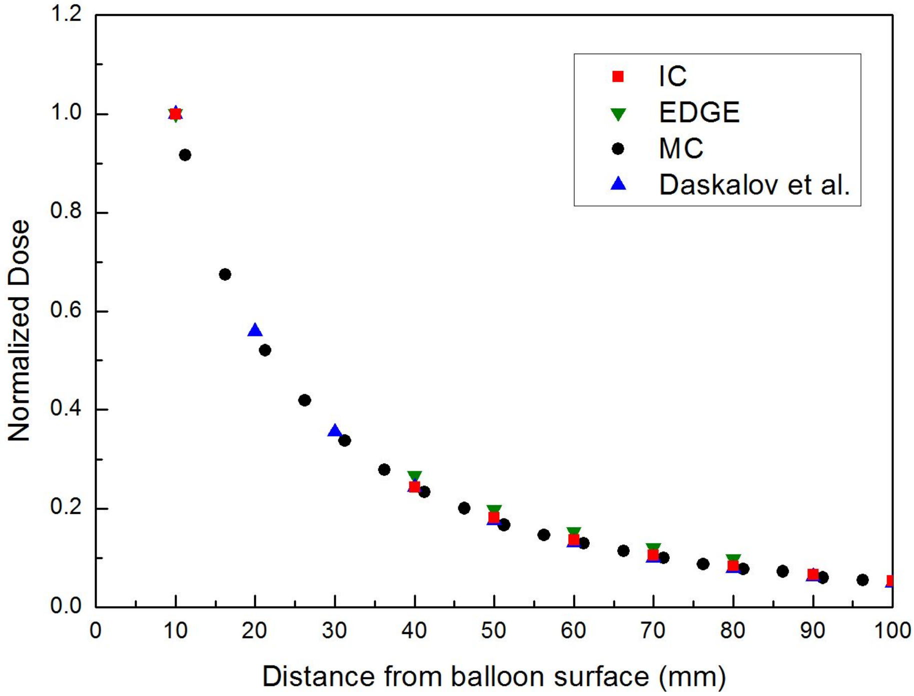

FIG. 5. Comparison of IC measurement with EDGE, MC simulation, and Daskalov et al. data for 0% iodine concentration. All of the value was normalized to 10 mm distance from the balloon surface

2. Dose perturbation

Figure 6 shows IC-measured and MC-calculated dose distributions for BPD of 50 mm (a) and 100 mm (b) with and without a pacemaker. The curves were normalized to 34 Gy at 10 mm from the balloon surface. Only the MC doses were available inside the pacemaker, which were calculated along the interface line between the substrate and battery. There was a large dose enhancement inside the pacemaker. Compared to those without a pacemaker, the doses with a pacemaker were increased by 1.1-7.1 Gy for BPD of 50 mm and 0.7-2.6 Gy for BPD of 100 mm. For low-energy photons, photoelectric absorption increases with increasing atomic number. Therefore, the dose increase is probably due to the relatively high atomic number of silicon substrate (Z = 14), titanium capsule (Z=22), and battery which consisted of iodine (Z = 53) and iron (Z = 26). In contrast, there was a dose decrease beyond a pacemaker. The amount of dose reduction at 10 mm beyond a pacemaker was approximately 1.0 Gy for BPD of 50 mm and 0.3 Gy for BPD of 100 mm. As distances from the pacemaker to points of measurement increase, the amount of dose reduction decreases and becomes almost no difference beyond 50 mm. In Figure 6, the balloon was filled with water only (i.e., no contrast).

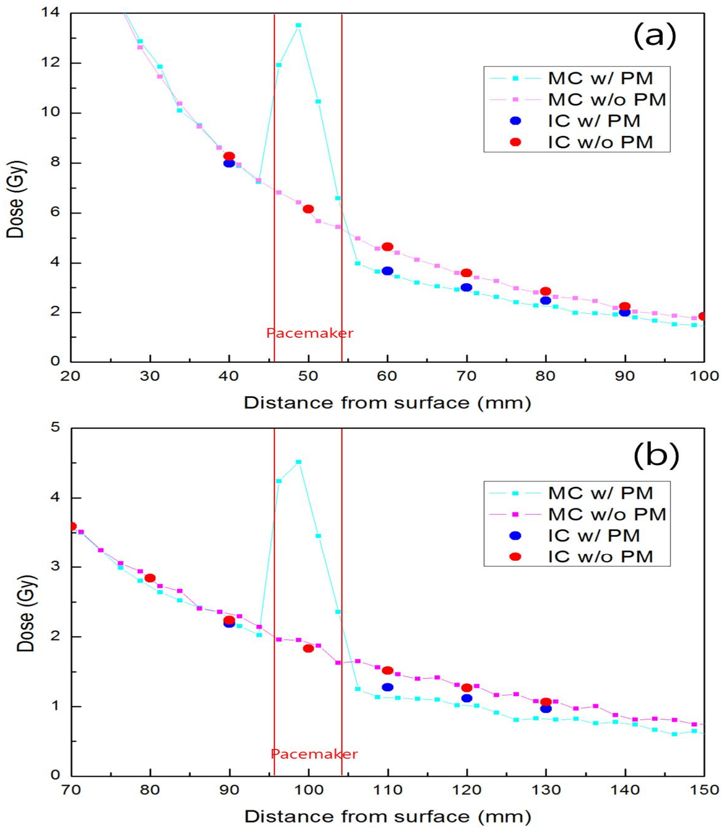

FIG. 6. The dosimetric effect of pacemaker presence (noted as "w/ PM") compared with pacemaker absence (noted as "w/o PM"). Doses were represented as a function of distance from balloon surface for (a) BPD = 50 mm and (b) BPD = 100 mm setup. Dose was normalized as 34 Gy at 10 mm distance from balloon surface. Monte Carlo simulation was performed as well as ion-chamber measurement (square – MC simulation, circle – IC measurement). Note that the dose scoring and measurement were performed along pacemaker midline and vertical solid line indicated the pacemaker placement region

Figure 7 shows the iodine contrast and different component (substrate and battery) effects on MC-calculated dose distributions where 0%, 2.5%, 5.0%, 7.5% and 10% concentrations of contrast medium in the balloon were assumed with and without a pacemaker. Vertical red lines indicate where a pacemaker was placed. All the data were normalized to the dwell time under the no contrast condition to deliver 34 Gy at 10 mm from the balloon surface for BPD of 50 mm (Fig. 7(a) and (b)) and 100 mm (Fig. 7 (c) and (d)). For each BPD, dose distributions through the substrate and battery were separately calculated. A higher dose was delivered to the battery than the substrate due to the high-Z components of battery. The attenuation by iodine contrast medium contributed approximately 0.5% - 4.0% dose reduction at the concentrations investigated in this study.

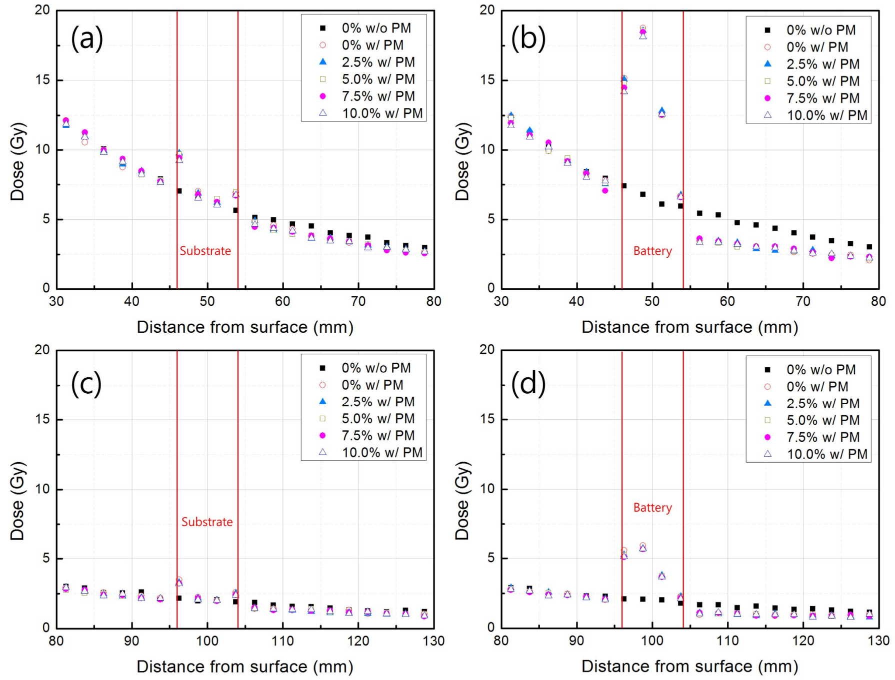

FIG. 7. Monte Carlo simulation showing the variation of dose as a function of distance from balloon surface for different iodine concentration (noted as "0%, 2.5%, 5.0%, 7.5%, and 10.0%") in pacemaker presence (noted as "w/ PM") and absence (noted as "w/o PM") situations. Dose was normalized as 34 Gy at 10 mm distance from balloon surface under the no contrast condition. Dose was scored through (a) substrate and (b) battery in BPD = 50 mm setup; Dose was scored through (c) substrate and (d) battery in BPD = 100 mm setup. Vertical thick line indicated the pacemaker placement region

Figure 8 shows the corresponding variations of dose perturbation factor. The dose perturbations through the substrate did not vary much and only the interface region with a titanium capsule made noticeable DPF about up to 1.5 as shown in Fig. 8(a) and (c). However, the dose perturbations through the battery varied significantly and doses in the middle of battery were increased by up to a factor of 3 (Fig. 8(b) and Fig. 8(b)), compared to doses without a pacemaker. Figure 8 also presents DPF variations for different concentrations of contrast medium. In general, the higher concentrations of contrast, the more are dose perturbations through a pacemaker although some of the data do not follow this tendency because of their small differences within uncertainty. With the iodine concentrations investigated in this study, the amount of DPF along the substrate ranged from 1.02 to 1.06 for 50 mm BPD and from 1.00 to 1.13 for 100 mm BPD. The corresponding variation along the battery ranged from 2.04 to for 2.75 for 50 mm BPD and from 1.82 to 2.85 for 100 mm BPD.

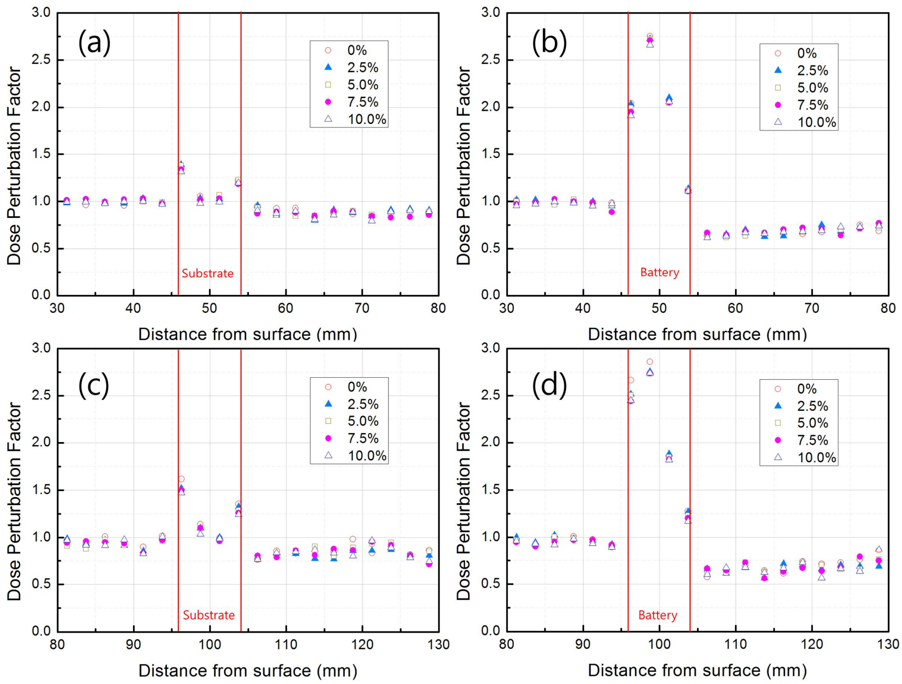

FIG. 8. Monte Carlo simulation showing the variation of dose perturbation factor as a function of distance from balloon surface for different iodine concentration (noted as "0%, 2.5%, 5.0%, 7.5%, and 10%") in pacemaker presence (noted as "w/ PM") and absence (noted as "w/o PM") situations. Dose was normalized as 34 Gy at 10 mm distance from balloon surface under the no contrast condition. Dose was scored through (a) substrate and (b) battery in BPD = 50 mm setup; Dose was scored through (c) substrate and (d) battery in BPD = 100 mm setup. Vertical thick line indicated the pacemaker placement region

Figure 9 shows MC-generated two-dimensional dose distributions for a 40 mm diameter balloon under the no contrast condition. The calculated doses were normalized to the dose (34 Gy) at 10 mm distance from the balloon surface. The doses more than 34 Gy were not plotted on the graph. The increased dose inside the pacemaker was clearly shown but much larger through the battery than the substrate. Dose attenuation by the pacemaker was also shown as dented isodose lines behind it but much less through the substrate.

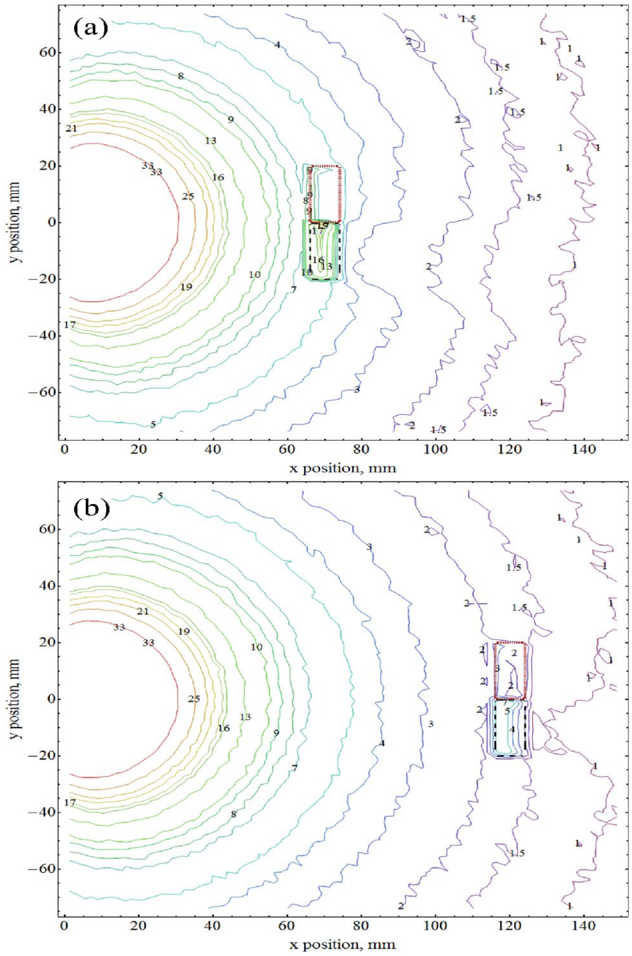

FIG. 9. Two-dimensional dose distribution for 0% iodine concentration normalized to 34 Gy at 10 mm distance from the balloon surface for (a) BPD = 50 mm and (b) BPD = 100 mm setup. The numbers on the axis represent distance (mm) from source center. The numbers labeled on the isodose lines represent absorbed doses (Gy) by different colors. The upper and lower dotted rectangles indicate the substrate and battery region, respectively

Figure 10 presents MC-calculated dose variation through a pacemaker battery for BPD of (a) 150 mm and (b) 200 mm with and without a pacemaker. The curves were normalized to 34 Gy at 10 mm from the balloon surface. The balloon did not contain iodine contrast for Figure 10 situation. The distances from balloon surface to a pacemaker reduced the dose to the pacemaker. The doses based on water-only calculation were 0.8-0.9 Gy for BPD of 150 mm, which was far below the TG-34 pacemaker tolerance dose (2.0 Gy). However, The doses with a pacemaker were 1.6-2.7 Gy (> 2.0 Gy) for BPD of 150 mm. At BPD of 200 mm, the doses with a pacemaker were 0.7-1.4 Gy (< 2.0 Gy). The TG-34 pacemaker tolerance dose was achievable at BPD of 200 mm.

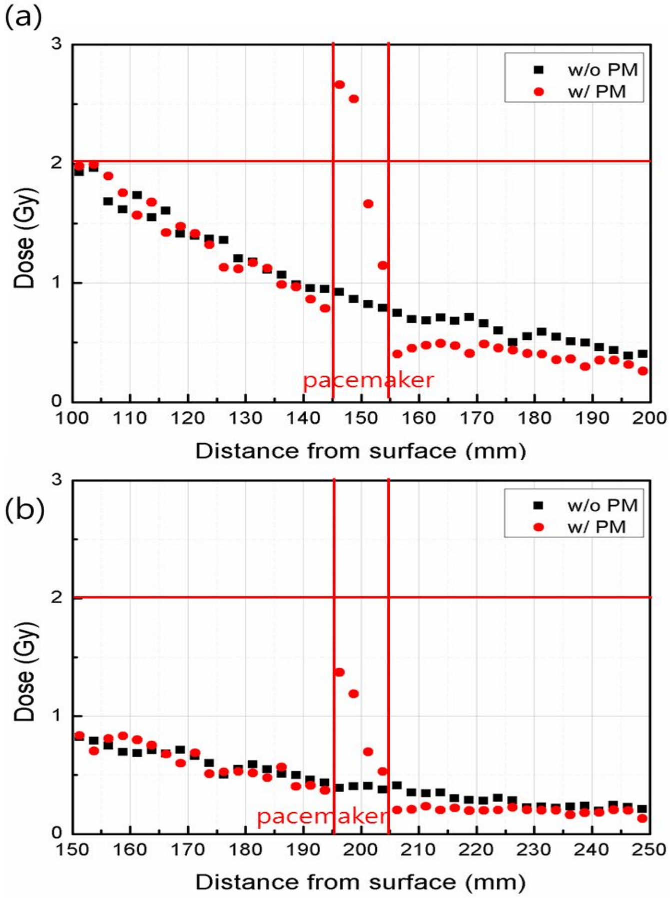

FIG. 10. Monte Carlo simulation showing the variation of dose as a function of distance from balloon surface for different balloon to pacemaker distances (BPD) in pacemaker presence (noted as "w/ PM") and absence (noted as "w/o PM") situations. BPD was (a) 150 mm and (b) 200 mm. Dose was normalized as 34 Gy at 10 mm distance from balloon surface under the no contrast condition. Dose was scored through battery. Vertical and horizontal thick line indicated pacemaker placement and TG-34 pacemaker tolerance dose respectively.

Figure 11 shows MC-generated dose variation involving lung and bone under the no contrast condition. The calculated doses were normalized to the dose (34 Gy) at 10 mm distance from the balloon surface. The placement of lung contributed to increase the dose of radiation over a pacemaker battery (DPF = 1.1~1.3). On the other hand, the dose was decreased when the radiation passes the bone tissues (DPF = 0.8~0.9). Since the large proportion of photoelectric interactions occurs in the Ir-192 lower energy beam, lung (a low-Z material) absorbed less energy while bone (a high-Z material) absorbed more energy than water prior to dose absorption to a pacemaker.

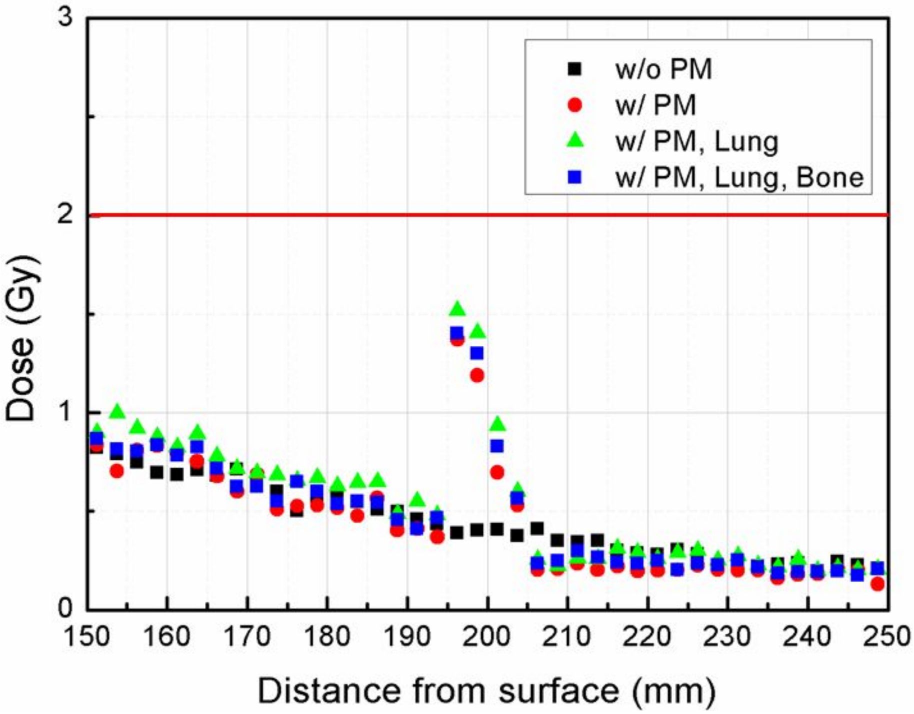

FIG. 11. Monte Carlo simulation showing the variation of dose as a function of distance from balloon surface for different balloon to pacemaker distances (BPD) in pacemaker absence, presence only, presence with lung, presence with lung and bone (noted a "w/o PM", "w/ PM", "w/ PM, Lung", "w/ PM, Lung, Bone" respectively) situations. BPD was 200 mm. Dose was normalized as 34 Gy at 10 mm distance from balloon surface under the no contrast condition. Dose was scored through battery. Horizontal thick line indicated the TG-34 pacemaker tolerance dose.

Discussion

Previous studies[8,10] regarding external beam radiotherapy reported that attenuation by a pacemaker and backscatter contribution were about -15.9% at 6 MV and -9.4% at 18 MV, and 2.8% at 6 MV and 3.4% at 18 MV, respectively and rapid dose changes were mainly observed in the battery region of pacemaker. However, the amount of attenuation determined by this study (Ir-192 HDR-based) was -21% for BPD of 50 mm and -16% for BPD of 100 mm. Because of predominantly low energy photon in Ir-192 and different pacemaker model used in this study, the different amounts of attenuations were measured. The backscatter contribution was hardly observed in our IC measurement and MC simulation probably due to a very short range of secondary electrons. It was reported that for kilo-voltage photons, backscatter dose enhancement vanishes within a few millimeters because of low-energy photo- and Auger electrons liberated by high-Z materials.[26]

Kim et al. estimated that in order to limit the pacemaker dose to 2.0 Gy the minimal distance from the surface of a 40 mm-diameter balloon was 105 mm.[12] Our measured and MC results without a pacemaker are 1.7 Gy at 105 mm. This discrepancy was similar to their measured verification (0.33±0.08 Gy). Therefore, our IC measured and MC results without a pacemaker coincided well with their measurements. Our MC simulation including a pacemaker and contrast medium for BPD of 100 mm predicted up to 2.3 Gy to the substrate and 5.9 Gy to the battery.

The dose increase was reduced by adding contrast medium (Figs. 7 and 8). Since the number of low-energy photons decreases with increasing iodine concentrations,[17] photoelectric absorption on the high-Z material inside a pacemaker becomes less dominant. The relative dose change appeared to be larger at 100 mm BPD than 50 mm BPD (Fig. 8) but was probably due to the much lower dose at 100 mm BPD.

Conservatively, battery dose, which highly contributes the dose to a pacemaker, was mainly concerned to determine clinically safe distance from balloon to the pacemaker. The BPD of 100 mm, which was calculated under water-only assumption[12], was not enough to achieve 2 Gy TG-34 tolerance dose. In this study, the clinical minimum distance of 200 mm was recommended. However, it has to be determined whether brachytherapy on modern pacemaker induces malfunction on these distances.

A partial volume of lung tissue and bony structures could be placed between the balloon and pacemaker (Fig. 11). As expected, the lung volume increase the dose to a pacemaker but bone volume decreased the dose to a pacemaker. Also, the lack of full scatter owing to the air and lung should be considered because it was reported to lead dose errors of up to 6% at 20 mm BPD.[13, 27] Therefore, the careful consideration involving lung and bone volume should be taken into account for pacemaker-implanted patients.

A multiple dwell position method for the balloon breast brachytherapy has been proven to improve the anisotropic dose distribution.[28] Since the radial dose distribution with multiple dwell positions does not significantly differ (< 3%) from that with a single source position[29] and we placed a pacemaker along the radial axis, the multiple dwell position method would not significantly affect our results.

Our MC results showed that there was a strong dose increase inside the battery of pacemaker even though it was not considered to be radiation-sensitive. More importantly, there was a dose increase even in the vicinity of the CMOS substrate interface with the titanium box and battery. This indicates that one should estimate a dose to the radiation-sensitive substrate in a more conservative way than before. In this study, modeling of pacemaker internal components was simplified. Any small metallic components excluded in the simulation could cause a dose increase that might trigger the malfunction on the CMOS substrate. Battery problems were exhibited in the previous study.[30] Thus, the battery dose increase shown in this study is also taken into account. A pacemaker malfunction in balloon breast brachytherapy should be further investigated because dose perturbations inside the pacemaker are more significant with low-energy photons of Ir-192.

Conclusions

Significant dose perturbations exist when introducing a pacemaker in Ir-192 HDR balloon brachytherapy. Although the CMOS substrate itself did not cause significant dose perturbations, the dose increase inside the battery and even at the substrate interface with the titanium capsule were significant. Therefore, BPD = 100 mm and 200 mm were estimated for safety of substrate and battery respectively. Also, one should be aware of possible higher doses to the pacemaker than TPS prediction when making a decision on a safe clinical distance from the balloon surface.

Appendix A. GEANT4/GATE input file

These input files are created to model the HDR microSelection Ir-192 brachytherapy source, MammoSite balloon, and pacemaker.

1. Main file

```
/control/execute verbose.mac
#=====================================================
# GEOMETRY
#=====================================================
/gate/geometry/setMaterialDatabase material/GateMaterials.db
# World
/gate/world/geometry/setXLength 400 mm
/gate/world/geometry/setYLength 400 mm
/gate/world/geometry/setZLength 400 mm
/gate/world/setMaterial Air
# Water Box
/gate/world/daughters/name                    waterbox
/gate/world/daughters/insert                  box
/gate/waterbox/geometry/setXLength 400 mm
/gate/waterbox/geometry/setYLength 400 mm
/gate/waterbox/geometry/setZLength 400 mm
/gate/waterbox/placement/setTranslation 0.0 0.0 0.0 mm
/gate/waterbox/setMaterial Water
/gate/waterbox/vis/setVisible 1
/gate/waterbox/vis/setColor blue
# Balloon
/gate/waterbox/daughters/name                 balloon
/gate/waterbox/daughters/insert        sphere
/gate/balloon/geometry/setRmin 0 mm
/gate/balloon/geometry/setRmax 20 mm
/gate/balloon/placement/setTranslation 0.0 0.0 0 mm
/gate/balloon/setMaterial Balloon5
/gate/balloon/vis/setVisible 0
/gate/balloon/vis/forceSolid
/gate/balloon/vis/setColor green
# Capsule
/gate/balloon/daughters/name                  capsule
/gate/balloon/daughters/insert                cylinder
/gate/capsule/geometry/setRmin 0 mm
```

```
/gate/capsule/geometry/setRmax 0.45 mm
/gate/capsule/geometry/setHeight 4.7 mm
/gate/capsule/placement/setTranslation 0.0 0.0 0.0 mm
/gate/capsule/setMaterial Stainless
/gate/capsule/vis/setVisible 1
#/gate/capsule/vis/forceSolid
/gate/capsule/vis/setColor green
# Iridium
/gate/capsule/daughters/name                    iridium
/gate/capsule/daughters/insert                  cylinder
/gate/iridium/geometry/setRmin 0 mm
/gate/iridium/geometry/setRmax 0.325 mm
/gate/iridium/geometry/setHeight 3.6 mm
/gate/iridium/placement/setTranslation 0.0 0.0 0.0 mm
/gate/iridium/setMaterial Iridium
/gate/iridium/vis/setVisible 1
/gate/iridium/vis/setColor red
/gate/iridium/vis/forceSolid
# Pacemaker
/gate/waterbox/daughters/name                   pacemaker
/gate/waterbox/daughters/insert                 box
/gate/pacemaker/geometry/setXLength 8 mm
/gate/pacemaker/geometry/setYLength 40 mm
/gate/pacemaker/geometry/setZLength 40 mm
/gate/pacemaker/placement/setTranslation 120 0 0 mm
/gate/pacemaker/setMaterial Titanium
/gate/pacemaker/vis/setVisible 1
/gate/pacemaker/vis/setColor red
# Silicon
/gate/pacemaker/daughters/name                  silicon
/gate/pacemaker/daughters/insert                box
/gate/silicon/geometry/setXLength 6 mm
/gate/silicon/geometry/setYLength 38 mm
/gate/silicon/geometry/setZLength 38 mm
/gate/silicon/placement/setTranslation 0 0 0 mm
/gate/silicon/setMaterial Silicon
/gate/silicon/vis/setVisible 1
/gate/silicon/vis/setColor white
# Battery
/gate/silicon/daughters/name                    battery
/gate/silicon/daughters/insert                  box
```

```
/gate/battery/geometry/setXLength 6 mm
/gate/battery/geometry/setYLength 38 mm
/gate/battery/geometry/setZLength 19 mm
/gate/battery/placement/setTranslation 0 0 -9.5 mm
/gate/battery/setMaterial Battery
/gate/battery/vis/setVisible 1
/gate/battery/vis/setColor yellow
/gate/geometry/setIonisationPotential Water 75 eV
/gate/geometry/setIonisationPotential Air 85.7 eV
#=====================================================
# PHYSICS
#=====================================================
/control/execute physics/egammaLowEPhys.mac
/gate/physics/Gamma/SetCutInRegion          world 2 mm
/gate/physics/Electron/SetCutInRegion      world 2 mm
/gate/physics/Positron/SetCutInRegion      world 2 mm
/gate/physics/Gamma/SetCutInRegion          waterbox 1 mm
/gate/physics/Electron/SetCutInRegion      waterbox 1 mm
/gate/physics/Positron/SetCutInRegion      waterbox 1 mm
/gate/physics/SetMaxStepSizeInRegion world 1 mm
/gate/physics/ActivateStepLimiter GenericIon
/gate/physics/displayCuts
#=====================================================
# DETECTORS
#=====================================================
/gate/actor/addActor                        DoseActor    doseDistribution
/gate/actor/doseDistribution/save                            output/pacemaker.txt
/gate/actor/doseDistribution/stepHitType                    random
/gate/actor/doseDistribution/attachTo                  waterbox
/gate/actor/doseDistribution/setPosition                   0 0 0 mm
/gate/actor/doseDistribution/setSize                        400 2.5 400 mm
/gate/actor/doseDistribution/setVoxelSize                 2.5 2.5 2.5 mm
#PTW chamber size is 5mm 5mm 5mm
/gate/actor/doseDistribution/saveEveryNSeconds          60
/gate/actor/doseDistribution/enableEdep                      true
/gate/actor/doseDistribution/enableUncertaintyEdep false
/gate/actor/doseDistribution/enableDose                      true
/gate/actor/doseDistribution/enableUncertaintyDose true
/gate/actor/doseDistribution/enableNumberOfHits        false
/gate/actor/addActor                          SimulationStatisticActor stat
/gate/actor/stat/save                       output/pacemaker_stat.txt
```

```
/gate/actor/stat/saveEveryNSeconds 60
#=========================================================
# INITIALISATION
#=========================================================
/gate/run/initialize
# Enable the following lines to display available and enabled processes
/gate/physics/processList Available
/gate/physics/processList Enabled
#=========================================================
# Source
#=========================================================
/control/execute source.mac
#=========================================================
# VISUALISATION
#=========================================================
#/control/execute visu.mac
#=========================================================
# START BEAMS
#=========================================================
# JamesRandom Ranlux64 MersenneTwister
/gate/random/setEngineName MersenneTwister
/gate/random/setEngineSeed 1000000000000
# /gate/random/verbose 1
# /gate/source/verbose 0
/gate/application/noGlobalOutput
/gate/application/setTotalNumberOfPrimaries 1000000000000
/gate/application/start
```

2. Source file

```
#=========================================================
# BETA
#=========================================================
/gate/source/addSource                        beta2
/gate/source/beta2/gps/particle        e-
/gate/source/beta2/setActivity                10 Ci
/gate/source/beta2/setForcedUnstableFlag true
/gate/source/beta2/setForcedHalfLife          6378998.4 s
/gate/source/beta2/gps/type                   Volume
```

```
/gate/source/beta2/gps/shape                  Cylinder
/gate/source/beta2/gps/ang/type       iso
/gate/source/beta2/gps/radius                 0.325 mm
/gate/source/beta2/gps/halfz                  1.8 mm
/gate/source/beta2/gps/centre                 0. 0. 0. cm
/gate/source/beta2/attachTo                   iridium
/control/execute                      source/Ir192_beta2.mac
#===========================================================
# Gamma #2
#===========================================================
/gate/source/addSource                        gamma2
/gate/source/gamma2/gps/particle      gamma
/gate/source/gamma2/setActivity               10 Ci
/gate/source/gamma2/setForcedUnstableFlag true
/gate/source/gamma2/setForcedHalfLife         6378998.4 s
/gate/source/gamma2/gps/type                  Volume
/gate/source/gamma2/gps/shape                 Cylinder
/gate/source/gamma2/gps/ang/type      iso
/gate/source/gamma2/gps/radius                0.325 mm
/gate/source/gamma2/gps/halfz                 3.6 mm
#Please note that above one is not "height", "halfz"
/gate/source/gamma2/gps/centre                0. 0. 0. cm
/gate/source/gamma2/attachTo                  iridium
/control/execute                      source/Ir192_photon2.mac
/gate/source/list
```

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Abstract (in Korea)

국문초록

목적: 고선량율 근접방사선치료를 이용한 유방 부분 방사선조사시 인공심장박동기를 삽입한 환자에서 발생할 수 있는 선량변화를 연구한다.

방법: 몬테카를로(Monte Carlo) 시뮬레이션을 이용해 Ir-192 고선량율 근접방사선치료와 인공심장박동기에 대한 선량분포를 계산한다. 풍선으로부터 인공심장박동기까지의 거리(BPD:Balloon to Pacemaker Distance, 50, 100, 150, 200 mm)와 풍선에 삽입되는 아이오딘 조영제 양(부피 대비 2.5, 5.0, 7.5, 10.0%)을 바꾸어 계산을 수행한다. 폐와 뼈 조직을 삽입하였을 때 인공심장박동기에 전달되는 선량변화를 관찰한다. 이온 전리함을 이용한 선량측정을 통해 몬테카를로 결과를 검증한다.

결과: 인공심장박동기 없이 균일한 물 속에서 몬테카를로와 이온 전리함 실험 결과는 BPD=100 mm 까지 기존의 출간된 결과와 2%이내로 일치함을 확인할 수 있었다. 인공심장박동기를 포함한 결과도 계산과 측정은 일치하였다. 몬테카를로 결과는 배터리의

선량이 최대 3 배까지 증가함을 보였다. 기판의 선량은 유의미하게 증가하지 않았으나 티타늄 캡슐과 접한 기판의 선량은 70%까지 증가하였다. 아이오딘 조영제는 인공심장박동기에 전달되는 선량은 최대 9%까지 감소시켰다. 폐 조직은 인공심장박동기에 선량을 증가시켰고 (DPF:1.1~1.3) 뼈 조직은 인공심장박동기에 선량을 감소시켰다 (DPF:0.8~0.9).

결론: 인공심장박동기와 조영제로 인한 불균질성 및 근접방사선치료선원의 낮은 에너지로 인하여 인공심장박동기에 전달되는 선량은 달라진다. 따라서 풍선과 인공심장박동기의 최소안전거리를 수립하기 위해 근접방사선치료 환자의 경우 인공심장박동기에 대한 선량변화는 반드시 고려되어야 한다. 본 연구에서는 기판이 고장을 일으킬 경우 BPD = 100 mm, 배터리가 고장을 일으킬 경우 BPD = 200 mm 가 최소안전거리로 추정되었다. 이에 따라 유방 근접방사선치료시 인공심장박동기가 삽입된 환자의 치료방법 및 인공심장박동기 위치를 결정할 수 있다.

색인어 : 삽입용 인공심장박동기, 유방 근접방사선치료,

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