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Evaluation of organ doses following high dose rate (HDR) brachytherapy of breast cancer: a Geant4 Monte Carlo simulation study

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Abstract. This study aimed to evaluate the absorbed doses received by the organs at risk (OARs) following Iridium-192 (^{192}Ir) high dose rate (HDR) brachytherapy of the left breast. The MIRD5 adult female anthropomorphic phantom, readily available in the Geant4 Monte Carlo package was used. However, the left breast was modified from 195 to 145 cm^3, to represent a breast following lumpectomy. Left breast was chosen due to its higher cancer occurrence than the right breast. The HDR sources were constructed with an outer cylindrical dimension of 4.5 mm (length) × 0.9 mm (diameter). Various influencing parameters were studied, i.e. catheter arrangement (single versus dual plane), source inter-dwell distances (5 versus 10 mm), and different radionuclides, i.e. Cobalt-60 (^{60}Co) and ^{192}Ir, by delivering a total treatment dose of 32 Gy to the left breast. Absorbed doses to the OARs (e.g. left lung, heart, right breast, spleen, etc.) were then evaluated. A maximum left lung dose of 1.5 Gy was recorded, while doses to the other OARs were all below 1 Gy. The treatment using dual plane catheter arrangement contributed to a slightly higher dose to the OARs, despite equal dose to the breast. There was no dose difference between different inter-dwell distances used in this study. ^{60}Co resulted in a slightly higher left lung dose than that of ^{192}Ir, while the results were the opposite for the other OARs. HDR brachytherapy allows high dose to be delivered to the breast within a short period of time, with minimal absorbed doses to the OARs.

1. Introduction
Breast cancer is the world's most common cancer involving women [1], with more than 1 million incidences in 2002 and more than 400,000 deaths worldwide [2]. The standard of care for breast cancer treatment includes surgical removal of the tumor and adjuvant therapies, i.e. local irradiation with systemic therapies (e.g. biological agents, hormonal therapies and chemotherapy) [3].

High dose rate (HDR) interstitial brachytherapy has been investigated in selected patients as a potential single radiotherapy technique, i.e. partial breast irradiation, following tumorectomy or lumpectomy [4], with the idea to minimize morbidity, optimize the treatment plan and maintain the treatment outcomes. Commonly used radionuclides include, Iridium-192 (^{192}Ir) ($\bar{E}$ = 0.38 MeV, half-life, $t_{1/2}$ = 73.8 d) and Cobalt-60 (^{60}Co) ($\bar{E}$ = 1.25 MeV, $t_{1/2}$ = 5.26 y). Similar to external beam radiotherapy of the breast, the main organs at risk (OARs) include the other breast, lungs and heart. Estimating the dose to the OARs prior to the treatment is crucial, so a well-planned treatment can be delivered, and overexposure to the OARs can be avoided. Nonetheless, direct dose measurement of the OARs involve further unnecessary surgical procedure, hence, is not a feasible and recommended technique.

Geant4 is one of the latest Monte Carlo (MC) code packages that provides accurate probability estimation of radiation events. It allows flexible manipulation of the geometry, for various medical physics researches. In this study, the absorbed dose received by the OARs following HDR treatment on the left breast was assessed using the Geant4 MC simulation. This was done by estimating the absorbed dose using different catheter arrangements, source inter-dwell distances and radionuclides.

2. Methodology

2.1. *The MIRD5 phantom*

The study was performed using Geant4.9.6.p03 [5, 6] advanced example *human_phantom*. The phantom was adopted from MIRD Pamphlet 5, with height and weight of 174 cm and 70 kg, respectively [7]. Female phantom equipped with both breasts (each with a volume of 194 cm^3) was selected [8]. However in this study, the left breast volume was reduced to 145 cm^3, to represent a breast following lumpectomy, as in Figure 1. The left breast was chosen due to its higher cancer occurrence than the right breast [9].

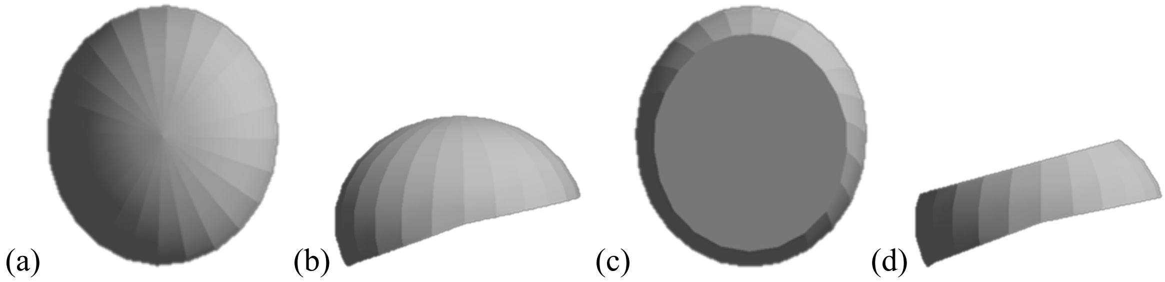


Figure 1. The phantom's left breast before ((a) anterior and (b) superior views) and after ((c) anterior and (d) superior views) lumpectomy.

2.2. *The ^{192}Ir sealed source*

The MicroSelectron HDR (Nucletron®, Elekta, Stockholm, Sweden) ^{192}Ir source was simulated [10]. The 3.6 mm (length, *l*) × 0.65 mm (diameter, *d*) cylindrical ^{192}Ir core (22.42 g.cm^{-3}) encapsulated with 4.5 mm (*l*) × 0.9 mm (*d*) stainless steel (8.02 g.cm^{-3}) was modeled as in Figure 2.

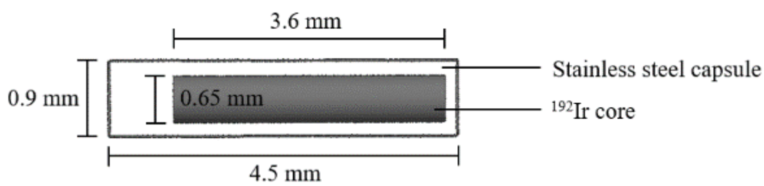


Figure 2. The microSelectron HDR ^{192}Ir source as modeled using the Geant4 package.

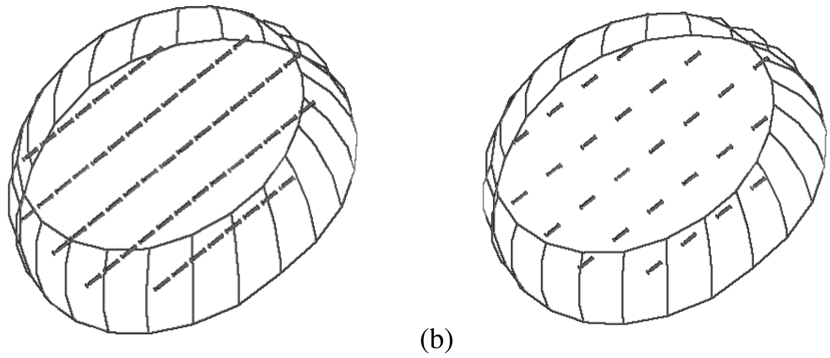
2.3. *Difference in treatment techniques*

A dose of 32 Gy was prescribed to the left breast. Four different treatment techniques were studied, i.e. single and dual plane catheter arrangements, each with 5 and 10 mm inter-dwell distances. The most peripherally located sealed source was kept at a minimum of 10 to 15 mm from the skin, to limit the skin dose and ensure that the radiation is contained within the breast volume.

For every technique used, 10^7 disintegrations were generated and repeated three times, to obtain a standard deviation of less than 1 %. The mean energy (MeV) deposited to each OARs was normalized to the energy deposited to the left breast. These normalized values were used to obtain the dose to all the OARs, by multiplying the values with the dose prescribed to the left breast, i.e. 32 Gy.

All simulations were later repeated by changing the ^{192}Ir to ^{60}Co, using similar source geometry. The decay of these radionuclides was modeled by utilising the Geant4 Radioactive Decay component. Low Energy Electromagnetic Package [11], based on the Livermore Evaluated Data Libraries was adopted to model the electromagnetic interactions of photons and electrons. The threshold of production of secondary particles was fixed to 1 mm.

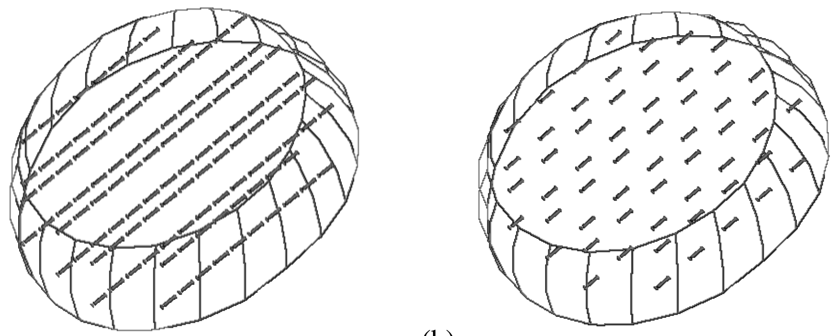
2.3.1. Single plane catheter arrangement with 5 and 10 mm inter-dwell distances. For single plane arrangement, 5 catheters were placed in parallel across the center of the breast volume, with a separation of 15 mm between each other. The inter-dwell distances between each source's stopping point was set to 5 mm (Figure 3a). The simulation was later repeated by changing the inter-dwell distance to 10 mm (Figure 3b).



(a) (b)

Figure 3. The anterior-superior view of the left breast for single plane catheter arrangement with (a) 5 and (b) 10 mm inter-dwell distances, as modeled using the Geant4 package.

2.3.2. Dual plane catheter arrangement with 5 and 10 mm inter-dwell distances. For dual plane arrangement, a total of 10 catheters were placed in parallel across the breast volume (5 catheters to each plane, i.e. superficial and deep), with a separation of 14 mm between each plane. Similar to the single plane technique, a separation of 15 mm was applied between each catheter of similar plane. The inter-dwell distances between each source's stopping point was set to 5 mm (Figure 4a). The simulation was later repeated by changing the inter-dwell distances to 10 mm (Figure 4b).



(a) (b)

Figure 4. The anterior-superior view of the left breast for dual plane catheter arrangement with (a) 5 and (b) 10 mm inter-dwell distances, as modeled using the Geant4 package.

3. Results & Discussions

The left breast volume was reduced from the initial value, to represent the breast following lumpectomy (breast conserving surgery). Two different radionuclides were used in this study, i.e. ^{192}Ir and ^{60}Co. Both radionuclides have different types and energies of decay emissions. The simulations were carried out for four different treatment techniques, i.e. single and dual planes, each with 5 and 10 mm inter-dwell distances.

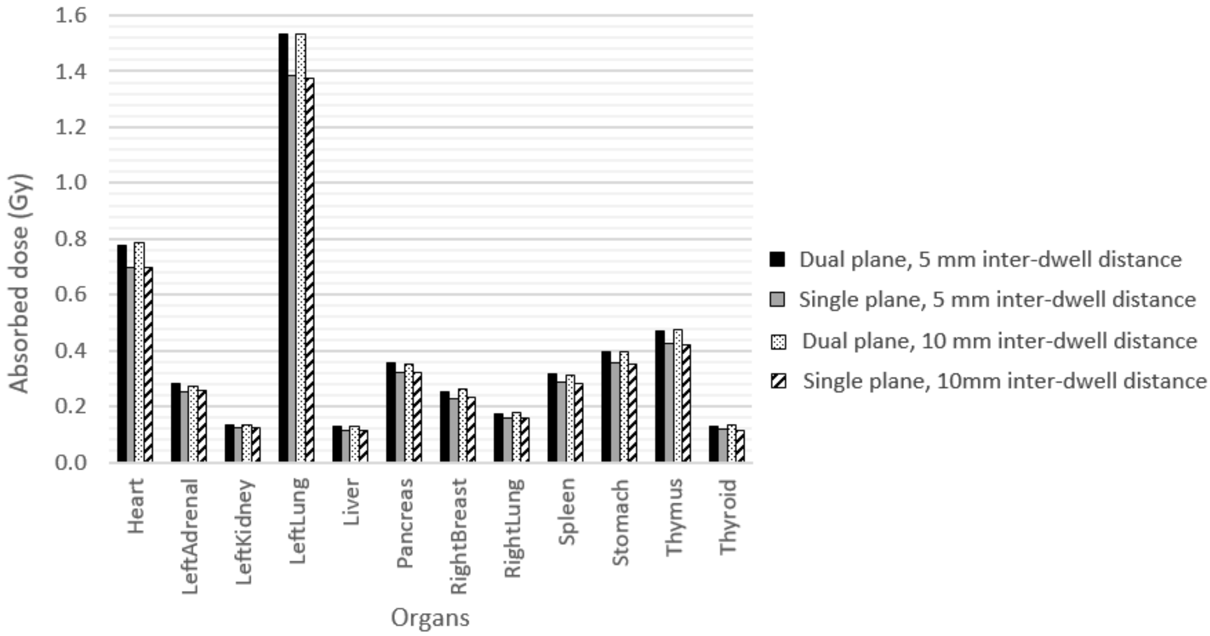


Figure 5. The absorbed dose to OARs with different treatment techniques using the ^{192}Ir source.

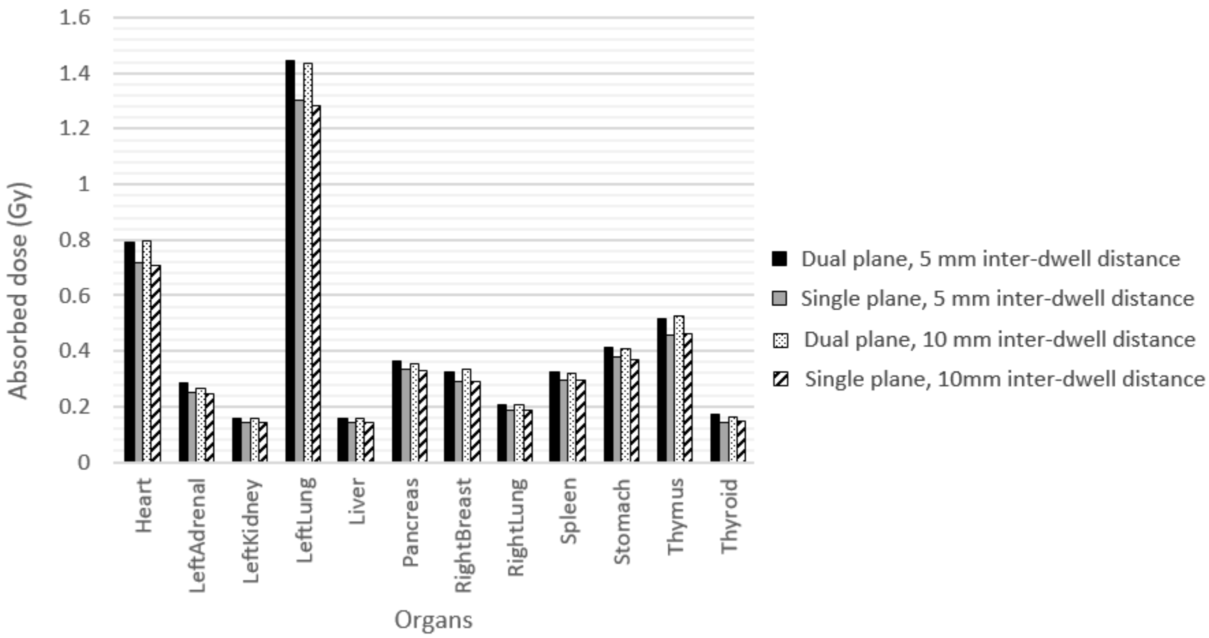


Figure 6. The absorbed dose to OARs with different treatment techniques using the ^{60}Co source.

From this study, it was found that ^{192}Ir and ^{60}Co deliver nearly the same absorbed dose to the OARs, while delivering similar prescribed dose to the left breast. Based on Figure 5 and 6, the absorbed dose delivered to the OARs by ^{60}Co were found to be slightly higher compared to ^{192}Ir, except for the left lung, where the dose was higher when ^{192}Ir was being used. This may be due to different decays of the two radionuclides. As ^{60}Co emits higher gamma energy (1.17 MeV) than ^{192}Ir (0.32 MeV), the organs that are located further from the left breast received higher absorbed dose when ^{60}Co is being used. However, since the beta energy of ^{192}Ir (0.67 MeV) is higher than ^{60}Co (0.32 MeV), a significant portion of the emitted beta particles managed to escape the left breast and deposit their energy into the left lung, compared to ^{60}Co, where most of the beta particles were absorbed by the left breast. These findings are in agreement with previous studies that compared the dose to OARs from ^{60}Co and ^{192}Ir sources [12], as well as the effect of various distances between these sources and the OARs [13].

The dual plane treatment technique delivers significantly higher absorbed dose to the OARs compared to the single plane technique, i.e. 1.54 and 1.38 Gy, respectively, for the left lung, and 0.78 and 0.70 Gy, respectively, for the heart. Thus, absorbed dose reduction of 9.9 % to the left lung and 10.5 % to the heart can be made, when the single plane treatment technique is being used.

There was no significant difference between the absorbed dose received by the OARs for 5 and 10 mm inter-dwell distances. This can be seen in both the single and dual plane treatment techniques. This finding may be due to the small difference between the inter-dwell distances (only 5 mm).

4. Conclusion

Interstitial HDR brachytherapy following lumpectomy can be considered reasonably safe, as the absorbed dose received by the OARs were found to be significantly low (less than 1 Gy), while the maximum absorbed dose recorded by the left lung was only 1.5 Gy. ^{60}Co shows better dose sparing effect towards the left lung compared to ^{192}Ir. However, ^{192}Ir delivers relatively much lower absorbed dose to the other OARs compared to ^{60}Co. Our study showed that, different number of treatment plane can greatly affect the absorbed dose to the OARs, while the difference in the inter-dwell distances does not affect the absorbed dose. However, a reduction in the number of catheter arrangement or plane may increase the duration of the treatment, even with similar prescribed dose to the breast.

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