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Dose Modification factors (DMF) Evaluation in MammoSite Breast Brachytherapy Using Monte Carlo Simulation

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ABSTRACT

Background & Objective: Partial Breast Irradiation (PBI) targets the tissue surrounding the tumor in breast cancer brachytherapy. Dose distribution can be affected by the type of radiation source, tumor depth, which alters backscatter, and by the concentration of contrast agents used for imaging. These factors may modify the dose delivered to the targeted area. Both ^{192}Ir and ^{60}Co sources are commonly used in PBI, and understanding how these factors interact is essential for accurate dose delivery and treatment optimization. Dose modification factors (DMFs) can be used to quantify these effects. The objective of this study is to evaluate the effect of tissue heterogeneity on the dose delivered to the 1-cm tumor margin and to calculate a dose modification factor relative to a homogeneous model.

Materials & Methods: Monte Carlo simulations were performed using a 30 cm water-equivalent spherical phantom and a 4 cm diameter MammoSite balloon applicator. HDR ^{60}Co and ^{192}Ir sources were placed inside the balloon. DMF was defined as the ratio of the dose rate at 1 cm from the balloon surface under full-scatter conditions to the dose rate when a limited tissue thickness existed beyond the prescription point. Tissue thicknesses ranged from 0 to 10 cm, and contrast agent concentrations varied from 0% to 25%.

Results: Dose reductions of approximately 5% for ^{192}Ir and 1% for ^{60}Co were observed when no tissue was present beyond the prescription depth. At 25% contrast concentration, ^{192}Ir showed an additional 4% reduction, while the dose reduction for ^{60}Co remained below 0.5% across all contrast levels.

Conclusion: The study emphasizes the importance of accounting for backscatter loss and contrast-induced attenuation, particularly for ^{192}Ir, to prevent underdosing. Applying DMF is essential for accurate treatment planning in surface-adjacent breast tumors undergoing MammoSite brachytherapy.

Keywords: MammoSite Brachytherapy, Partial Breast Irradiation, Dose Modification Factor, Contrast Agent, Monte Carlo Simulatio

1. Introduction

Breast cancer remains the most common malignancy among women, with approximately 14% lifetime risk. Despite advancements in treatment, the survival rate without recurrence stands at 80-89% (1). In Iran, it accounts for 24.4% of female cancers and ranks as the fifth leading cause of cancer-related deaths (2, 3). While surgery remains the primary treatment, adjuvant radiotherapy significantly improves outcomes (4). One approach, Partial Breast Irradiation (PBI), targets only the tissue surrounding the tumor and is especially beneficial in early-stage breast cancer (5-12). Among PBI techniques, the MammoSite brachytherapy method is widely used. It involves placing a silicone balloon catheter into the tumor cavity after lumpectomy, with the balloon filled with a contrast solution to achieve a near-spherical shape (13). The size of the balloon is similar to the tumor size, usually between 4 cm and 6 cm. A high-dose-rate (HDR) radiation source, typically ^{192}Ir or ^{60}Co, is inserted into the center of the balloon to deliver 34 Gy in 10 fractions over 5–7 days. Each fraction delivers 3.4 Gy to a 1 cm margin beyond the balloon surface. The total treatment typically takes 5 to 7 days.

One challenge with MammoSite arises in patients with superficial tumors, where the distance to skin is minimal, raising the risk of exceeding skin dose limits (14-16).

Moreover, the treatment planning system commonly uses the TG-43U1 algorithm, which assumes an infinite water medium under full-scattering conditions. However, breast tissue is often small, and iodine-based contrast agents within the balloon alter dose distributions (17-21). These factors can lead to significant dose deviations, particularly near the prescription line.

To quantify these effects, a Dose Modification Factor (DMF) is introduced,defined as the ratio between the planned and actual dose rates (22).

$$DMF = \frac{\dot{D}_{planned}}{\dot{D}_{delivered}}$$

It is important to note that most of the time, cancer reoccurs near the original tumor bed, where this procedure aims to treat. Consequently, it is crucial to achieve reliable dose predictions (23).

This study aims to investigate the impact of limited backscatter and contrast agent concentration on DMF in MammoSite brachytherapy using MCNP simulations.

2. Materials and Methods

In this study, Monte Carlo N-Particle (MCNP) simulations were used to evaluate the effects of limited tissue thickness and varying contrast concentrations on dose distribution for both ^{60}Co and ^{192}Ir HDR sources. The simulation model consisted of a spherical water phantom with a 30 cm diameter (represented by the blue sphere), mimicking breast tissue, and a 4 cm MammoSite balloon positioned at its center (represented by the orange sphere). The cylindrical HDR radioactive sources were placed along the X-axis at the center of the balloon (Figure 1).

To measure the dose at the prescription line, a hypothetical detector cell (purple sphere) was placed 1 cm from the balloon's surface. This distance corresponds to the planning target volume (PTV) in this method. Finally, the entire setup was placed inside a cubic air phantom (the gray cube) measuring 200 cm on a side. The material inside this phantom was assumed to be dry air (79% N, 20% O, and 1% Ar by weight). Particles were not tracked beyond this air phantom.

The high-dose rate (HDR) Iridium-192 source, based on the BEBIG model, consists of a core with a height of 3.5 mm, a radius of 0.3 mm, and a density of 22.4 g/cm^3. This core is encapsulated within a steel layer. Radioactivity is assumed to be uniformly distributed within the source core. For the ^{192}Ir source, only the 10 most significant energy levels contributing to the spectrum were considered.

The HDR Cobalt-60 source (Co0.A86 model) is also cylindrical, with a height of 3.5 mm, a base radius of 0.25 mm, and a density of 8.9 g/cm^3. It is encapsulated in a capsule with an outer diameter of 5 mm and an outer radius of 0.5 mm. The ^{60}Co source emits photons at two distinct energies, 1.33 MeV and 1.17 MeV, each with a 50% probability.

Further details are available in Ghorbani et al (24) and on the BEBIG Medical GmbH (25).

The balloon's silicone catheter and source encapsulation were not modeled to simplify the simulation.

The absorbed dose in the detector cell was calculated using the F6 tally in MCNPX 2.6.0. The F6 tally reports energy deposition per unit mass (MeV/g). Dose outputs from the F6 tally were directly used without explicit normalization to source activity. Since the analysis focused on the dose modification factor (DMF), which is defined as the ratio of doses under different conditions, any normalization factor cancels out. Therefore, the reported DMF values are independent of absolute dose normalization.

A total of 5×10^7 particle histories were simulated. No user-defined energy cut-off was specified, and the default MCNPX cut-off values were applied. Each simulation was performed once, and the relative error reported by MCNPX for the F6 tally was within acceptable limits (<1%), ensuring the statistical reliability of the results. Therefore, repeated independent runs were not required.

The dose was calculated for varying tissue thicknesses, ranging from 0 cm to 10 cm beyond the prescription line. Additionally, the concentration of the contrast agent inside the balloon was varied from 0% to 25%.

In the first approach of our study, we initially positioned the Mammosite balloon at the center of a water phantom. In this configuration, the tissue thickness beyond the detector cell was 27 cm, providing conditions for "full-scatter."

Next, we incrementally moved the water phantom downwards by 1 cm along the z-axis. While keeping the balloon and water phantom sizes unchanged, this adjustment altered only the tissue thickness beyond the balloon. At each step, we recorded the dose rate at the prescription line for varying tissue thicknesses. This process was repeated until the distance between the surface of the Mammosite balloon and the water-air interface was reduced to 1 cm, representing the condition with no tissue thickness beyond the detector cell—termed "without backscatter."

To assess the tissue backscatter effect, we calculated a dose-modifying factor by dividing the dose rate under "full backscatter" conditions by the dose rate at each tissue thickness.

For the second approach, we used the same experimental setup, however this time, with the balloon fixed at the center of the water phantom to ensure full backscatter. The only variable altered was the material inside the balloon.

The contrast agent used for this study was Iohexol ($C_{19}H_{26}I_3N_3O_9$), marketed as OMNIPAQUE, a non-ionic, water-soluble radiographic contrast agent. It has a molecular weight of 821.14, with iodine accounting for 46.36% of its weight. While the Iohexol solution also contains 1.21 mg of Tromethamine and 0.1 mg of Sodium

calcium edetate per milliliter, their effects were considered negligible for this study (26, 27).

We examined Iohexol concentrations of 5%, 10%, 15%, 20%, and 25% by volume, as recommended by the manufacture. The densities of these solutions and additional details were taken from Bassel Kassas's study (28).

Initially, the balloon was filled with water (0% contrast agent concentration), which corresponds to the condition assumed by the treatment planning system. Subsequently, we replaced the water with contrast agent solutions of varying concentrations, updating the elemental composition accordingly, and recorded the dose rate at the prescription line for each concentration.

To quantify the effect of contrast agent concentration on dose rate, the recorded dose rate for each concentration was divided by the dose rate obtained when the balloon contained water (0% concentration). This allowed us to evaluate the impact of contrast agent concentration on the delivered dose.

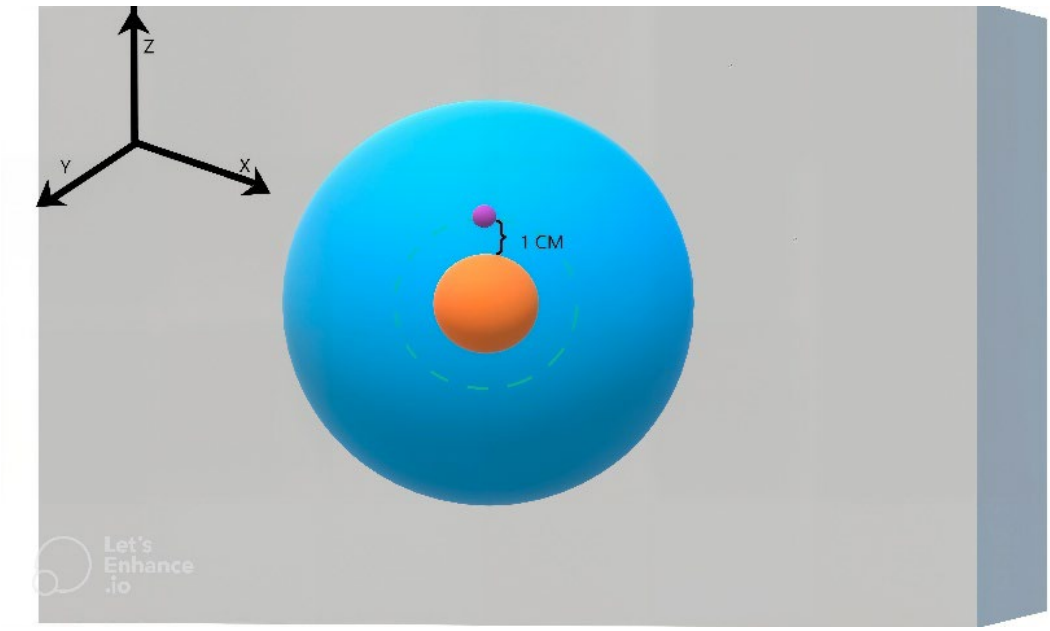

Figure 1. Model setup with water phantom, MammoSite balloon, detector at prescription line, and surrounding air cube (**Prepared by Authors, 2025**).

3. Result

For the first approach, the DMF values for ^{60}Co and ^{192}Ir were calculated for tissue thicknesses ranging from 0 cm to 10 cm beyond the prescription line (Table 1). Although it is uncommon to find tissue exceeding 5 cm from the prescription line in clinical settings, the range was expanded to 10 cm to demonstrate the extent of tissue required for complete scattering and to ensure thoroughness.

According to Table1, when no tissue was present beyond the prescription line (only 1 cm of breast tissue existed between the balloon's surface and the skin), the DMF was 1.012 for ^{60}Co and 1.052 for ^{192}Ir. This means that even when the procedure's requirement of maintaining at least 1 cm between the balloon's surface and the skin was satisfied, there was still an estimated 5% reduction in the dose rate due to lack of full scatter when using ^{192}Ir HDR source, and nearly 1% of dose rate reduction when using ^{60}Co.

Additionally, the simulations indicated that 5 cm of breast tissue thickness beyond the prescription line was still insufficient to achieve full scatter when using ^{192}Ir HDR source.

Figure 2 illustrates the DMF value on the y-axis for the two sources, while the x-axis shows the tissue thickness in centimeters.

As depicted in Figure 2, on the left side of the graph, when the balloon is positioned closer to the surface, the dose modification factor (DMF) exceeds one. This indicates that the treatment planning system overestimates the delivered dose compared to the actual amount. As we move towards the right side of the graph—where tissue thickness beyond the prescription line increases (corresponding to a tumor located deeper within the tissue)—the DMF approaches one. This implies that, in these conditions, the dose calculated by the treatment planning system more closely.

Furthermore, Figure 2 highlights that the rate of change in DMF is more pronounced for the ^{192}Ir source compared to the ^{60}Co source. This can be attributed to the higher photon energy of ^{60}Co, which reduces the significance of backscatter effects at short distances, because photons

pass rapidly through tissue. While the backscatter effect becomes more noticeable with increased tissue thickness (around 16 cm), it remains relatively minor for ^{60}Co. In contrast, the lower photon energy of ^{192}Ir results in a greater sensitivity to backscatter, making this effect more pronounced in clinical scenarios.

The current model assumes complete symmetry, with air surrounding the entire 3D geometry and a uniform tissue thickness (radius) at every angle. However, in real clinical situations, tissue distribution around the source is not uniform. Rather than a constant tissue thickness, varying tissue thicknesses exist at different angles around the tumor. By averaging the DMF across multiple angular sectors with varying thicknesses of tissue, an overall average DMF can be derived. Moreover, additional techniques for dose optimization can be developed by using various dwell positions for the HDR source to accommodate this dose modification.

In the second approach, as indicated in Table 2, the dose rate reduction for ^{60}Co across all contrast material concentration is less than 0.5%. However, for the ^{192}Ir source, the effect of contrast agent concentration is more substantial, with the dose rate decreasing by approximately 4% when the concentration is increased to 25%. This effect could become more significant if a larger balloon filled with a highly concentrated contrast agent is employed.

Figure 3 illustrates the impact of varying contrast material concentrations on dose rate. The y-axis represents the ratio of the dose rate in the presence of contrast material to the dose rate with only water in the balloon. Therefore, the maximum value on the y-axis is normalized to 1. The x-axis shows different concentration values.

As depicted in Figure 3, changes in the dose rate for ^{60}Co remain minimal across all concentrations. This result can be attributed to the high photon energy emitted by ^{60}Co, where Compton scattering is the dominant process. Since this scattering process is mainly independent of the atomic number, the dose rate remains relatively stable regardless of changes in contrast material concentration for ^{60}Co.

The American Association of Physicists in Medicine (AAPM) Task Group 40 guidelines permit a ±15% variation in the delivery of the prescribed dose for intracavitary brachytherapy (29). However, reductions in dose due to insufficient scatter, compounded by the use of contrast material, can introduce significant uncertainties in treatment accuracy.

Table 1. DMF values for different amounts of tissue thickness (cm) beyond the prescription line for ^{60}Co and ^{192}Ir.

Tissue Thickness (cm)	^{192}Ir∗(10^{-5})	^{60}Co∗(10^{-4})
10 cm	1.002085	1.000726
9 cm	1.002629	1.000859
8 cm	1.003487	1.001066
7 cm	1.004314	1.001352
6 cm	1.005620	1.001673
5 cm	1.007312	1.002092
4 cm	1.009647	1.002746
3 cm	1.013451	1.003537
2 cm	1.018986	1.004837
1 cm	1.029594	1.007245
No Backscatter	1.051760	1.011973

Table 2. The percentage of dose rate reduction for ^{60}Co and for ^{192}Ir different contrast concentrations (%).

Contrast Concentration (%)	^{192}Ir	^{60}Co
5%	-0.75%	-0.073%
10%	-1.59%	-0.2%
15%	-2.36%	-0.3%
20%	-2.93%	-0.37%
25%	-3.53%	-0.47%

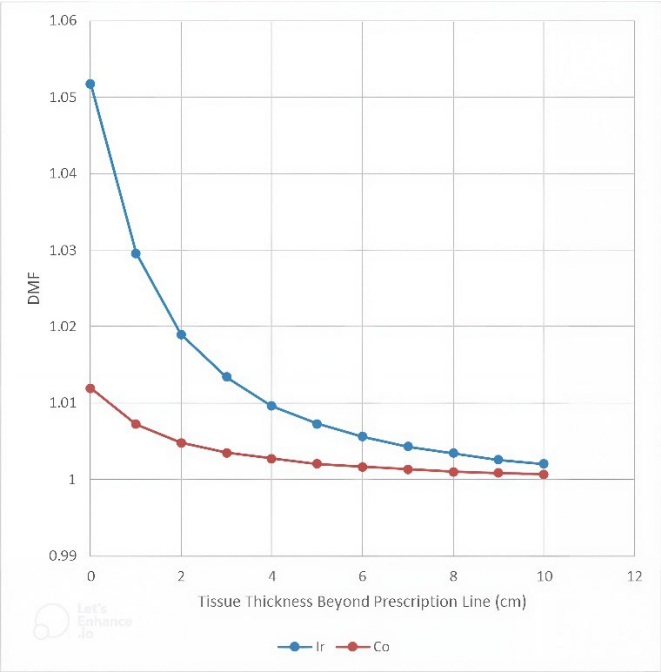

Figure 2. DMF values for different amounts of tissue thickness for ^{60}Co and ^{192}Ir (**Prepared by Authors, 2025**).

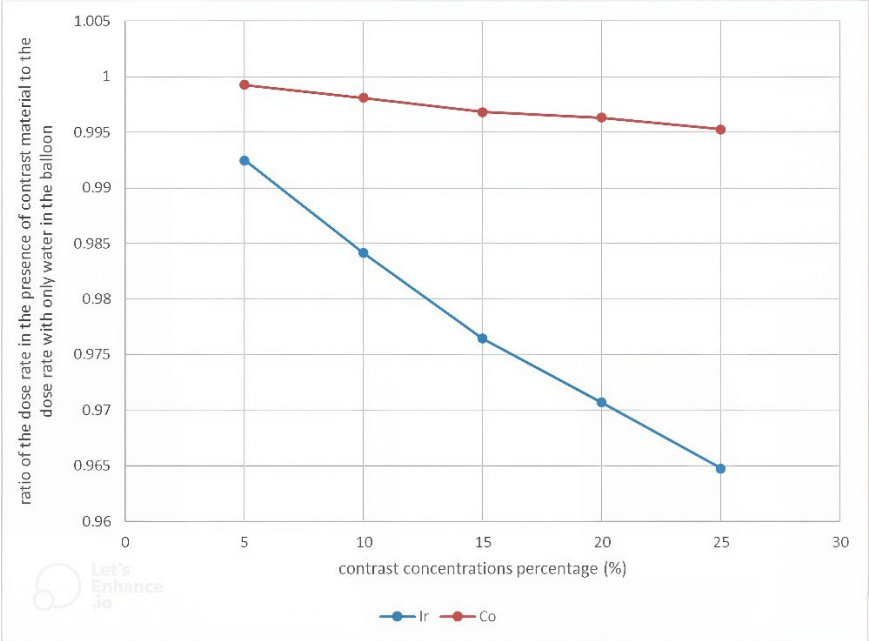

Figure 3. Dose rate reduction for different concentrations for ^{60}Co and ^{192}Ir (**Prepared by Authors, 2025**).

4. Discussions

This study provides valuable insights into the dosimetric characteristics of ^{192}Ir and ^{60}Co sources in MammoSite brachytherapy. The observed dose rate reductions—approximately 5% for ^{192}Ir and 1% for ^{60}Co under conditions of minimal tissue thickness beyond the prescription line emphasize the clinical relevance of backscatter effects. For ^{192}Ir, the pronounced sensitivity to both tissue thickness and contrast agent concentration underscores the need for precise adjustments in clinical settings to avoid under-dosing at the prescription line. At the same time, the reductions in dose rate associated with increased contrast agent concentrations further underscore the trade-off between imaging clarity and dosimetric accuracy. This indicates the need to carefully optimize contrast agent levels to ensure accurate dose delivery while maintaining adequate imaging quality.

The clinical implications of these findings are significant in patients with superficial tumors, where even a modest reduction in prescription-line dose could compromise tumor control probability. This suggests that

in certain scenarios, treatment plan modifications—such as adjusting dwell times and source positions (in multilumen catheters), or contrast levels—may be necessary to ensure adequate tumor coverage while avoiding unintended under-dosage.

While these results provide clinically meaningful insights, several limitations should be noted. The omission of the balloon's silicone catheter and source encapsulation simplified the model. Still, it should be acknowledged as a limitation, as these components may have a minor effect on scatter and dose distribution in clinical practice. Furthermore, this study did not include direct validation against experimental or clinical data. This limitation primarily arises from a lack of access to dedicated brachytherapy phantoms and measurement facilities. Nevertheless, the simulation methodology follows established Monte Carlo approaches that have been widely applied and validated in previous MammoSite and brachytherapy studies, which supports the credibility of the results presented here. Future investigations incorporating patient-specific geometries, experimental measurements, or clinical data will be essential to strengthen the applicability of these findings.

When placed in the context of prior research, these findings extend the understanding of brachytherapy applicators. For example, our DMF results for ^{192}Ir are consistent with those reported by Kassas et al **(22)**, which supports the validity of our approach. However, unlike their study, which only considered ^{192}Ir and did not assess the effects of contrast agents, our analysis broadened the scope by including both ^{192}Ir and ^{60}Co sources and quantifying the impact of contrast concentration. Similarly, in contrast to Pearson et al **(30)**, who investigated the Contura multilumen applicator with ^{192}Ir, this study examined the MammoSite single-lumen applicator, which has an inherently symmetric dose distribution. Moreover, while Pearson's work primarily focused on the dose modification factor (DMF), our analysis expanded the scope by evaluating both isotopes and explicitly assessing the influence of contrast agent concentration. These differences highlight the complementary nature of the two studies and illustrate the additional clinical insights our work provides.

Finally, beyond these specific considerations, this study is also limited by its use of idealized models that assume uniform distributions of tissue and contrast, and may not accurately reflect the complex anatomical heterogeneities encountered in clinical settings. Future work should incorporate more complex geometries and patient-specific anatomical data to enhance the applicability of these results. Additionally, while ^{60}Co's longer half-life (~5.3 years) reduces the need for frequent source replacements, its higher photon energy necessitates more extensive shielding, which must be considered in clinical deployment.

5. Conclusion

Our Monte Carlo simulations demonstrated a dose rate reduction of approximately 5% for ^{192}Ir and 1% for ^{60}Co when the tissue thickness beyond the prescription line was minimal. For ^{192}Ir, the dose rate further decreased from 0.7% to 4% as the contrast agent concentration increased from 5% to 25%. In contrast, the dose reduction for ^{60}Co remained below 0.5% across all tested concentrations. Although these variations fall within the ±15% tolerance range recommended by AAPM Task Group 40, the results highlight the clinical importance of considering tissue heterogeneity and contrast material effects in treatment planning. Ignoring these factors—especially in ^{192}Ir -based treatments—can lead to under-dosing at the prescription line and compromise therapeutic outcomes. Overall, our findings suggest that ^{60}Co offers greater dosimetric stability under variable tissue and contrast conditions, making it a favorable alternative to ^{192}Ir in certain clinical scenarios. Additionally, the significantly longer half-life of ^{60}Co (approximately 5 years) minimizes the frequency of source replacements, thereby reducing logistical and financial burdens. However, due to the higher photon energy of ^{60}Co, its use requires enhanced shielding—roughly twice as much as that needed for ^{192}Ir. Appropriate shielding strategies must therefore be implemented to ensure the safety of both patients and staff.

6. Declarations

6.1 Acknowledgments

I extend my heartfelt gratitude to Ms. Pouyanrad for her invaluable guidance with MCNP coding. I would also like to express my deepest thanks to my mother and sister for their unwavering emotional support and encouragement, without which this accomplishment would not have been possible.

6.2 Ethical Considerations

This study is simulation-based research and does not involve human or animal subjects. Therefore, ethical approval is not required.

6.3 Authors' Contributions

Conceptualization, A.S. and M.Sh.; methodology, A.S.; software, A.S.; validation, A.S., M.Sh.; formal analysis, A.S.; investigation, A.S.; resources, A.S.; data curation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S., M.Sh.; visualization, A.S.; supervision, M.Sh.

6.4 Conflict of Interest

The authors have no conflict of interest.

6.5 Fund or Financial Support

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.6 Using Artificial Intelligence Tools (AI Tools)

The authors declare that no artificial intelligence tools were used in this study.

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