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A Dosimetric Comparison Study for Blood Irradiation Employing Different Medium and Algorithms in Clinical Linear Accelerator

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Objective: To identify a suitable approach for blood irradiation other than the commonly used water medium and to study the impact of different algorithm dose computations.

Methods: Water is the commonly used medium for blood irradiation. In this study computed tomography scans were taken with locally made blood irradiation phantoms other than water, by using air, rice powder and thermocole using parallel beam for 25 Gy. Plans were recalculated for different algorithms such as collapsed cone (CC), Monte Carlo (MC) and pencil beam (PB). The dose–volume parameters and measured doses were collected and analyzed for each medium and algorithm.

Findings: The monitor unit (MU) for rice powder and water are close (2461±57 and 2469±61, respectively), with a maximum dose of 28.0±1.8 and 28.0±1.9 Gy. The PB algorithm resulted in lower monitor unit values regardless of the medium used, generating values of 2418, 2406, 2382, and 2362 for water, rice powder, air, and Thermocol, respectively. A significant increase in dose was observed irrespective of the medium used when the MC algorithm was employed, with a maximum of 30.26 Gy in rice powder; a smaller dose was used when the CC algorithm was employed, with 26.3 Gy in water medium. The average maximum doses of all groups were equal using the one-way Anova statistical test. Regarding the impact of field size, rice powder appears to have consistent doses across various field sizes, with slight increases as field size grows, which is similar to water.

Novelty/Applications: While water is the conventional medium, this study highlights the potential benefits of rice powder, such as eliminating the risks associated with bubble formation and water spillage, which can lead to equipment malfunction and safety hazards. Although previous studies have explored rice powder as a bolus and tissue-equivalent material, this study uniquely applies this knowledge to blood irradiation, an area where rice powder has not been thoroughly investigated.

Keywords: computed tomography, collapsed cone, Monte Carlo, pencil beam, monitor units, MU, treatment planning station.

Introduction

TA-GVHD is a rare complication of transfusion that may occur when transfused lymphocytes are viable and one of the following is present in the recipient. The recipient is either immunosuppressed or there is a partial HLA matching between the transfused product and the recipient. Immune attack is mediated by the transfusion donor's viable T cells, either through direct destruction of host cells or via inflammatory cytokines that activate other immune cells, including natural killer (NK) cells, macrophages, and other lymphocytes. In such a scenario, blood irradiation has the potential to eliminate the ability of lymphocytes to mount an immune response by preventing its ability to replicate, serving as the sole genuinely efficient method for such disease prevention.[1] The primary approach to blood irradiation involves exposing the blood to gamma photons using specialized irradiator units containing either one of the radioactive isotopes, that is, Cobalt 60 or cesium 137.[2] Due to the unavailability of such devices in many departments, it is quite unusual to use the clinical linear accelerator machine for such procedures. Numerous research studies have indicated that the

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irradiation of blood using clinical linear accelerators is feasible, providing cost savings and allowing for the efficient utilization of existing facilities.[3,4] In our radiotherapy department we were using 6 MV photon energy Elekta Versa HD (Stockholm UK) for such an irradiation procedure. Blood irradiation is a standard practice in our department for bone marrow transplants. Our irradiation setup includes a specially designed perspex box with a lid, filled with water to deliver a 25 Gy dose uniformly, which will completely suppress the lymphocyte response.[5,6] Before the blood irradiation setup was initiated, the total monitor units were computed for the phantom using a water medium to deliver the prescribed dose at the isocenter for both anterior–posterior and posterior–anterior beams in our Monaco planning station (IMPAC Medical System, Inc., Maryland Heights, USA) using a collapsed cone (CC) algorithm. Additionally, dosimetric verification was conducted using a Semiflex chamber and Gafchromic irradiator indicator film to ensure accurate dose calculation.

Upon thorough examination of this method involving water, it becomes evident that there are several significant concerns that must be carefully addressed. The primary concern associated with the use of water in this method concerns the formation of bubbles, which could significantly impact the uniformity of dosage distribution. Another critical issue arises from the possibility of water spilling onto the machine's couch, as well as the motor and linac head, if not managed with the utmost care. Water spillage poses not only a risk to the integrity of the equipment but also introduces potential safety hazards for personnel operating the machine and patients undergoing treatment. If unnoticed, this ingress of water into sensitive components of the machine, such as the motor and linac head, can result in corrosion, electrical malfunction, and other operational inefficiencies, thereby necessitating costly repairs and down time. Given these concerns, particularly in the context of blood irradiation procedures, it becomes evident that addressing these challenges would require substantial investment. This includes the development and implementation of stringent protocols to prevent bubble formation and water spillage, alongside comprehensive training for personnel to ensure that they can manage these risks effectively. However, the complexity and cost associated with mitigating these issues make it clear that an alternative medium is highly desirable.

Rice powder can be used as a promising alternative for such procedures. Unlike water, it does not carry the risk of bubble formation or spillage. As a dry medium, it naturally eliminates the possibility of liquid-related hazards such as corrosion or electrical failure. Additionally, rice powder can provide a more uniform medium for dosage distribution, potentially improving the overall accuracy and safety of irradiation procedures. The shift to using rice powder would not only address the significant concerns associated with water but also streamline the process, reducing the need for extensive safety protocols and training while enhancing the reliability of the treatment. Numerous studies have focused on the dosimetric aspects of rice powder, examining its use as a bolus material and its viability as a tissue-equivalent material.[7–10] The results of this study consistently demonstrate the suitability of rice powder for various radiation applications, positioning it as a versatile and practical alternative to traditional water-based systems. Therefore, this study primarily investigates the viability of using rice powder as an alternative substrate, in place of water, for a faster and simplified workflow in blood irradiation.

Ensuring precise calculations is another crucial aspect of radiation therapy. The planning station employs various mathematical formulations and algorithms to achieve swift and accurate dose calculations. An optimal dose calculation algorithm can accurately represent the real dose distribution, thus minimizing uncertainty in plan evaluations. Different algorithms produce varying results when calculating in an inhomogeneous medium, with a more noticeable impact on computation compared to the changes observed in a homogeneous medium. Currently, various vendors are offering distinct algorithms for dose calculation. These algorithms operate using pre-set input radiation beam data obtained during machine commissioning. In our department, we have Monaco™ V 5.11 TPS for external beam radiotherapy treatment planning, which have PB algorithm, CC and MC for dose calculation. The CC algorithm employs various simplifications in the physics of radiation transport, allowing for computation times suitable for clinical application. In contrast, the pencil beam (PB) algorithm is highly efficient but has limitations in heterogeneous media due to utilizing a one-dimensional density correction, which fails to accurately capture the distribution of secondary electrons in materials with differing densities. The MC algorithm, in contrast, is presently considered to be one of the most sophisticated for dose computation.[11,12]

Existing research has primarily focused on computational algorithms and their performance, with limited investigations into the effects of different medium on blood irradiation. This study aims to fill this gap by comparing three distinct dose-calculation algorithms, namely, PB, CC, and MC, provided by a commercial treatment planning system, to assess their impact on various substrates for blood irradiation. Additionally, the study analyzes the influence of field size in conjunction with the medium. The study was conducted at our radiation oncology department using an Elekta HD versa linear accelerator and Monaco Planning station.

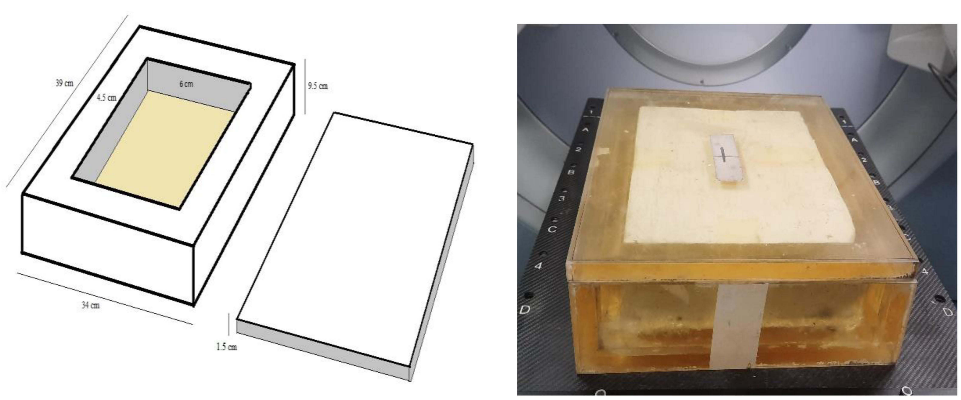
Materials and Methods

The study was conducted using a custom-built phantom at our hospital, following approval from the Institutional Research Committee of Kasturba Medical College and Kasturba Hospital. The Perspex phantom was fabricated with meticulous attention to detail, ensuring precise dimensions to facilitate accurate simulations. The internal dimensions of the phantom measure 30 cm x 25 cm x 6 cm, while the total dimensions are 39 cm x 34 cm x 10.5 cm, including a 1.5 cm thick upper lid. This design provides a secure and controlled environment for irradiation procedures (Figure 1). The dimensions were determined considerating the maximum field size capability of the linear accelerator, which is 40 cm x 40 cm at the isocentre, and the backscatter of effect of the radiation beam.

To simulate the placement of a blood bag, a 200 mL semi-fluid-filled balloon was strategically attached inside the phantom using micropore surgical tape, so that the movement was completely restricted in CT scanning for all four media. This setup closely replicates the conditions under which the blood bag would be exposed to radiation, providing a realistic model for study. Four different medium were chosen to fill the phantom, air, water, rice powder, and thermocol, to compare their effects on radiation exposure (Figure 2).

Precise radiation dose calculations in radiotherapy treatment planning systems require an accurate correlation between computed tomography image data and electron density values. A study conducted by Damilola et al found that the radiation attenuation parameters of soy flour were not significantly different from those of water.[13] In this study, the rationale behind selecting rice powder was its electron density, which closely resembles that of water, making it an ideal candidate for simulating soft tissue. On the other hand, thermocol was chosen due to its electron density being closer to air, offering a contrast in the study of radiological properties (Table 1). The electron density of this medium were calculated from the Monaco treatment planning station using the Philips CT scanner images and the respective Hounsfield units.[14]

Four separate CT simulations were conducted using a Philips Brilliance 16 Big Bore machine with a slice thickness of 3 mm. The simulations involved each medium air (without any medium), water, rice powder, and thermocole individually, to assess the differences in radiation interaction. Fiducial markers were carefully placed on the phantom, with one positioned anteriorly and two on the lateral sides, to mark the laser origin points accurately. The images obtained from the CT scans were then transferred to the Monaco planning station for further analysis.



a b

Figure 1 (**a**) Schematic diagram of blood irradiation phantom; (**b**) in-house phantom.

Figure 2 Material used for study: (**a**) rice powder; (**b**) thermocole.

The Monaco treatment system can be used for target delineation, registration and precise dose calculations with the help of different algorithms. In the Monaco planning station, version 5.11, the fluid-filled balloon was meticulously contoured as the target, along with separate contouring of the medium and phantom in each of the four CT images (Figure 3). Once the contouring process was complete, a 6 MV photon beam was configured in both anterior–posterior and posterior–anterior directions, ensuring the bag was positioned precisely at the isocentre in all setup medium. A field size of 35 × 35 cm² was employed using the source to axis distance technique. Calculations were performed across all media using different algorithms, such as the CC, MC, and PB, within the Monaco planning station. Each algorithm has its own pros and cons; for instance, the PB algorithm evidently did not account for the scattering geometry results in computing doses less accurately, yet it is faster than the MC algorithm.[15] Hence, a careful investigation of the accuracy of dose calculations using each beam data set and algorithm is always recommended. For each CT set, the total monitor units (MUs) for each field, along with the maximum dose (Dmax) and mean dose (Dmean) for the medium and target, were meticulously recorded using dose–volume histograms. One-way analysis of variance and Tukey's honestly significant difference (HSD) test were employed to calculate the statistical significance of p-values and assess the normality of the data for this study.

Furthermore, the study also investigated the effect of absolute dose across the different medium using a semiflex dosimeter in conjunction with the custom-built blood irradiation phantom. Field sizes of 10 x 10, 20 x 20, 30 x 30, and 40 × 40 cm² were utilized, with a source-to-skin distance of 95 cm and a monitor unit setting of 100. Meter readings were taken, and correction factors were applied to calculate the absolute dose for each field size and medium. To ensure accurate dose delivery, a RadTag® irradiation Gafchromic indicator film was employed. This film features a central dot that changes color upon irradiation, serving as a visual confirmation of radiation exposure of 25 Gy, and indicates whether the exposure was under or over the intended dose (Figure 4).

Table 1 Electron Density of Medium Used

Medium Used	Electron Density (g/cc)
Rice powder	0.93 ± 0.02
Water	1.0±0.03
Air	0.002 ± 0.002
Thermocole	0.030 ± 0.04

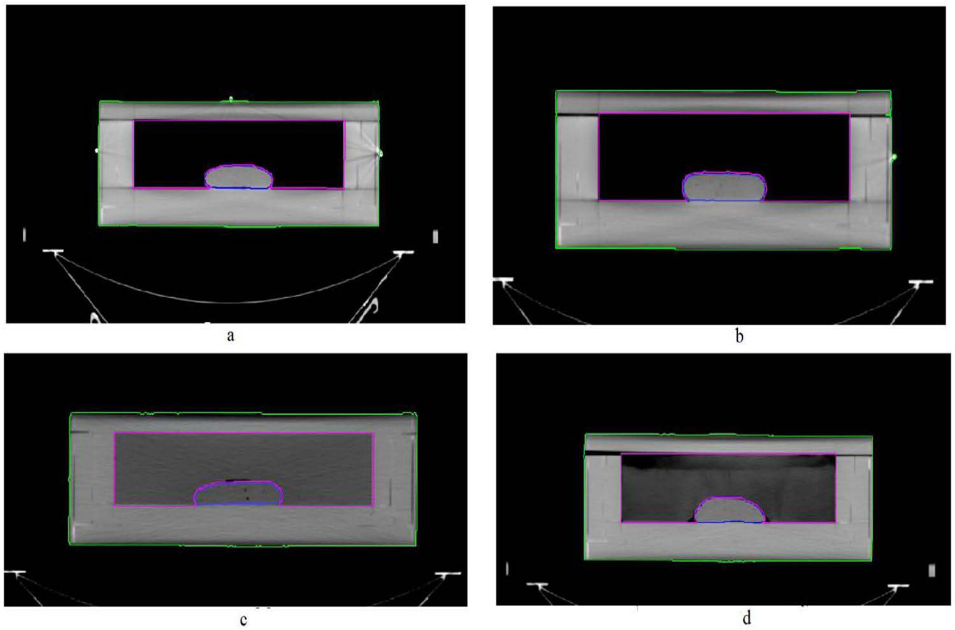


Figure 3 Axial CT view for different medium used for blood irradiation study: (a) air; (b) thermocole; (c) water; (d) rice powder.

Figure 4 Film indicator before (a) and after (b) irradiation (25 Gy).

Results and Discussion

There have been several studies dedicated to the technical aspects of the irradiation process, with minimal emphasis on the economic and managerial implications.[16–18] Petrov et al conducted a study utilizing existing equipment without requiring new investments or disrupting the clinical workflow of patients for blood irradiation. In their department, they employed rice grains as a medium to facilitate homogeneous dose distribution for blood irradiation, offering a unified procedure. Moreover, the study states that the choice of a water-equivalent rice medium satisfied the condition of a dose build-up effect.[19] However, it is noted that utilizing rice grains as a medium can leave a lot of voids; if rice powder is used instead, it will fit better and result in a more uniform dose. Although previous studies have investigated rice powder as a bolus and tissue-equivalent material, this work uniquely applies this knowledge to the domain of blood irradiation, an area where the use of rice powder has not been extensively examined In this study we were trying to evaluate the effectiveness of different materials, one of which was rice powder, which can be considered an alternate substrate for blood irradiation. A total of four CT images with different medium (air, thermocol, rice powder and water) data were taken up for comparison. Based on the treatment planning system's dose distribution, the majority of the build-up materials were successful in producing a uniform dosage distribution inside the acrylic box except in the air medium. With rice powder, the total MU was found to be more or less the same when compared with the water medium; similar comparable dose output is measured among the air and thermocole medium. The change in monitor unit with different substrates and algorithms is shown in Figure 5 and Table 2.

The study also focused on the comparative analysis of three different dose-calculation algorithms (PB, CC, and MC) provided by the Monaco™ V 5.11 TPS, specifically in the context of blood irradiation. This comparison in the context of different substrates, including the novel use of rice powder, is an innovative approach, particularly as it also considers the impact of field size on dose distribution. The pencil beam algorithm overestimates the dose, hence MU, relative to other algorithms because of its inefficient electron spread phenomenon. The MUs calculated using the PB algorithm were less (≤2406) than those calculated by other algorithms irrespective of the medium used. Less MU (2362) is noted in thermocole material, followed by air, rice powder and water. While the PB algorithm is highly efficient in terms of time taken for computation, its limitations in handling heterogeneous media are widely recognized.[20] The data from the study show that the measured MU from the PA beam in both air and thermocole was slightly higher compared to that of the AP beam. However, in the case of water and rice powder, it is the opposite. This difference is attributed to the influence of the couch, which has a higher electron density compared to air and thermocole but is lower when compared with water and rice powder along the posterior–anterior radiation path.

It is a known fact that, in the current clinical scenario, the MC algorithm is considered to be one of the gold standards, with the highest accuracy in terms of dose computation. The MC method has shown its precision in predicting dose distribution for radiotherapy treatment planning. However, its previous drawback of long computation times has impeded its widespread use in routine clinical settings. Nevertheless, improvements in computational algorithms designed specifically for radiotherapy calculations and upgrades in computer processor technology have significantly reduced the time required for MC simulations.[21,22] Regarding the doses observed (Table 3), it was found that MC tends to produce higher maximum doses (30.26 Gy) compared to PB and CC, while PB generally yielded lower mean doses to blood when compared to the other techniques, for all materials. It was also found that, using the PB algorithm, a higher dose was noticed in air (27.84 Gy) and thermocole (27.79 Gy). This may be due to its use of a one-dimensional density correction, which failed to accurately represent the distribution of secondary electrons in various density environments.[15]

For rice powder, the highest maximum dose (30.26 Gy) was noted with Monte Carlo, which is followed by CC (26.67 Gy) and PB (27.57 Gy). Similar trends were seen for water: Monte Carlo (30.2 Gy), PB (27.55 Gy), and CC (26.3 Gy), respectively. It is well noted that the observed dose amounts for air and thermocol were similar, just like those of rice

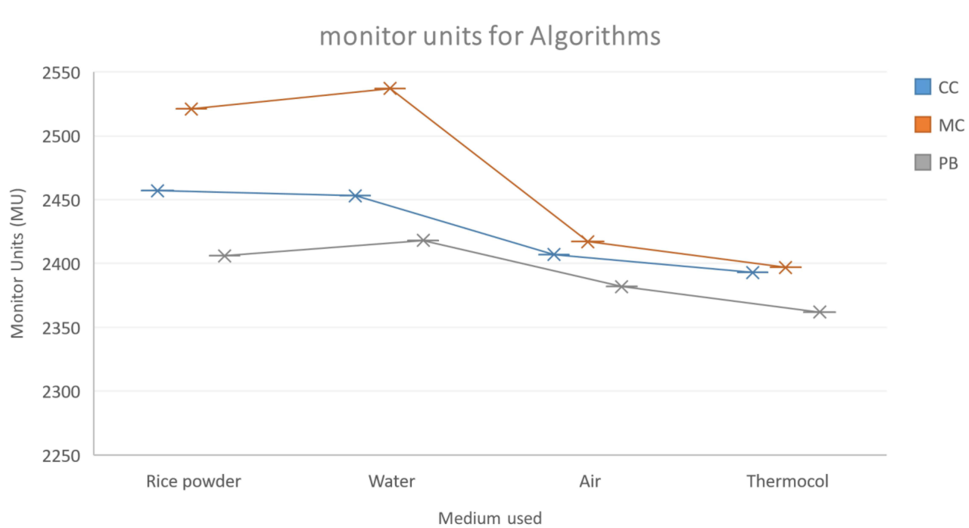


Figure 5 Impact on MU for different medium, with associated algorithms.

Table 2 Anteroposterior and Posterioanterior Beam MU for Different Algorithms and Medium

	Max Dose (Gy) (mean±SD)	Total MU (mean±SD)	PB		CC		MC		P-value (with water)
			AP	PA	AP	PA	AP	PA	
Rice powder	28.1±1.8	2461±57	1233	1173	1252	1205	1268	1253	0.99
Water	28.0±1.9	2469±61	1242	1176	1251	1201	1308	1229	0
Air	27.33±0.44	2402±18	1204	1178	1187	1220	1191	1226	0.95
Thermocole	28.0±1.2	2384±19	1183	1179	1175	1217	1187	1209	0.99

Abbreviations: Gy, Gray; SD, Standard Deviation; MU, Monitor Units, PB, Pencil Beam; CC, Collapsed Cone; MC, Monte Carlo.

Table 3 Doses Observed for Different Media and Algorithms Used

	Pencil Beam		Collapsed Cone		Monte Carlo	
	Max Dose (Gy)	Blood Mean Dose (Gy)	Max Dose (Gy)	Blood Mean Dose (Gy)	Max Dose (Gy)	Blood Mean Dose (Gy)
Rice powder	27.57	25.37	26.67	25.46	30.26	26
Water	27.55	25.48	26.3	25.42	30.2	26.13
Air	27.84	25.42	27.1	25.49	27.15	25.5
Thermocole	27.79	25.25	27	25.37	29.5	25.47

Abbreviation: Gy, Gray.

powder and water medium. The average maximum doses of all groups were assumed to be equal while using the Anova statistical test. In other words, the difference between the sample averages of all groups is not big enough to be statistically significant (p-value e0.908653). By using the Tukey HSD, there is no significant difference shown between the means of any pair shown in Figure 6. The normality assumption of the study was checked based on the Shapiro–Wilk test and all groups distributed normally.

The relative effectiveness or suitability of each medium for different field size on absolute dose was also measured and compared with the help of the semiflex chamber dosimetry system, as shown in Figure 7.

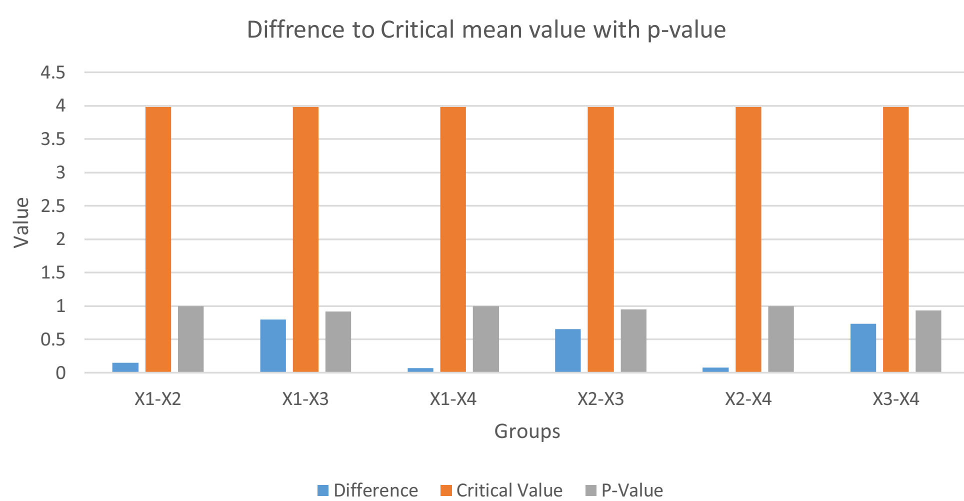


Figure 6 Statistical group-wise comparison of difference to critical mean with p-value.
Note: X1 rice powder; X2 water; X3 air; X4 thermocole.

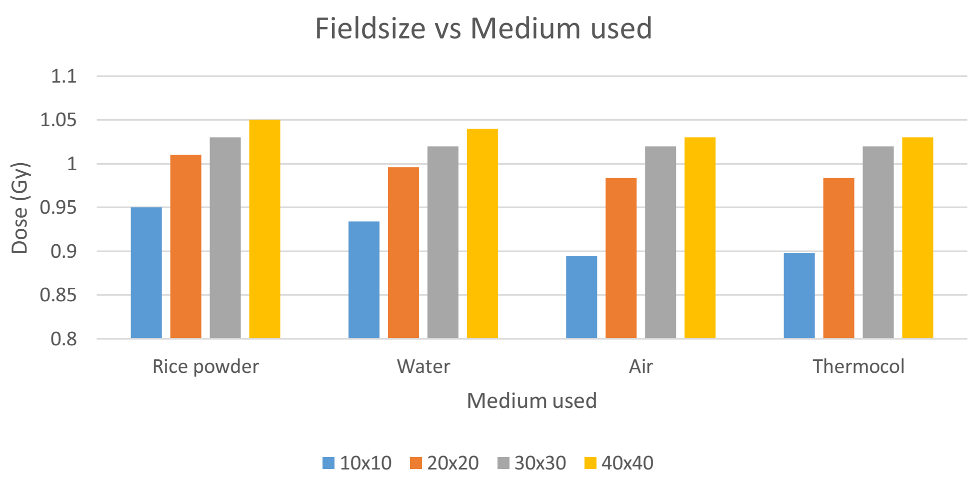


Figure 7 Impact on different field sizes using different media.

It was noted that, with increasing field size, the output dose for all medium increased proportionally.[23,24] Rice powder appeared to have consistent doses across various field sizes, with slight increases as the field size grew. Similarly, water demonstrated a comparable trend to rice powder (1.05 Gy), showing higher doses (1.04 Gy) as the field size expanded. Conversely, air indicated almost uniform doses across different field sizes, reflecting consistent dose delivery regardless of the field size. Thermocol also displayed uniform doses across various field sizes, like air. Rice powder could serve as a suitable medium for delivering scalable doses based on field size requirements, just like the water medium. In contrast, air and thermocol presented consistent doses across all fields sizes, making them more appropriate for applications where a uniform dose is needed irrespective of field size.

Increasing demand for blood irradiation in any radiotherapy department will definitely interfere with the routine treatment patient schedule. Using rice powder as a medium for blood irradiation has certain specific advantages, such as reducing setup time by up to two-thirds in comparison to water irradiation work.[4,25] Its cost-effectiveness and availability are other advantages. One of the major drawbacks with rice powder as a medium for irradiation, however, concerns practical considerations when handling and managing it, in comparison to water. Water is readily available, easy to handle, and does not require special preparation. On the other hand, rice powder needs to be properly prepared, managed, and stored to ensure consistency and safety. Another problem that may be encountered is contamination of blood products during irradiation setup. This can occur with water as well, even though the chances are very low. Contamination can be avoided by taking appropriate precautions and ensuring proper package of blood bags. All these factors should be taken into account when considering blood irradiation. The thermal property of rice powder compared to water is questionable, thus further research on this matter is advisable.

Future studies should focus on validating the dosimetric characteristics of rice powder across a broader range of radiation energies and treatment modalities to confirm its widespread applicability as a tissue-equivalent material. Examining the long-term stability and storage requirements of rice powder will be critical to ensuring its practicality in clinical settings, particularly in maintaining its dosimetric properties over time. Further expanding the investigation to include comparisons with other potential alternative media could identify the most effective substitute for water, providing a comprehensive evaluation of available options.

Conclusion

In this research, dosage computation for blood irradiation using PB, CC, and MC algorithms was quantitatively examined using various medium such as air, water, rice powder, and thermocol. The total monitor units for both rice powder and water were found to be nearly equivalent across all three algorithms and different field sizes. When comparing thermocol with other medium, its response closely matched that of air. It was observed that fewer monitor units were recorded in PB while more monitor units were noted in the MC algorithm regardless of the medium used. Additionally, the maximum dose was found to be higher when using the MC algorithm, especially using rice powder.

It has been observed that utilizing rice powder as a medium for blood irradiation offers notable advantages in terms of cost-effectiveness and availability of resources, as well as minimizing or no spillage onto machine components. Additionally, the setup time for blood irradiation is reduced when compared with the water medium. Consequently, it can be concluded that rice powder, due to its similarity in electron density to water, presents a viable alternative medium for blood irradiation.

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Disclosure

Sarath S Nair is the primary author. The authors have no relevant conflicts of interest to disclose for the present study.

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