International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 2026, 15(4), 110-129
https://www.scirp.org/journal/ijmpcero
ISSN Online: 2168-5444
ISSN Print: 2168-5436

Dosimetric Verification of Blood Component Irradiation Using a Clinical Linear Accelerator: Methodology and Quality Assurance

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How to cite this paper: Ibrahim, A.G., El-Bahkiry, H.S., Abbas, O., Ali, A.E., Radwan, R.M., Moustafa, M.F. and Mahmoud, D.G. (2026) Dosimetric Verification of Blood Component Irradiation Using a Clinical Linear Accelerator: Methodology and Quality Assurance. *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, **15**, 110-129.
https://doi.org/10.4236/ijmpcero.2026.154009

Received: October 3, 2026
Accepted: November 7, 2026
Published: November 10, 2026

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Abstract

Purpose: Irradiation of blood components is a standard protocol for preventing transfusion-associated graft-versus-host disease (TA-GVHD) in immunocompromised recipients. Utilizing a Linear Accelerator (LINAC) enhances quality assurance by providing precise dose delivery and uniform radiation distribution, ensuring both component efficacy and patient safety. **Materials and Methods:** This method uses a specific blood irradiation device, such as a linear accelerator to achieve lymphocyte suppression while preserving the integrity of other blood cells. The technical calibration protocol for blood irradiators includes a comprehensive assessment of absolute dose rate distribution throughout the blood bag. **Results:** Quality assurance (QA) for the Varian CL2100 CD linear accelerator was performed using only 6 MV photon energy. All measured parameters were following acceptance test specifications and exhibited favorable agreement with published tolerance values from comparable facilities. The measured central dose meets the standard protocol for 2500 cGy within the allowed ±5% measuring uncertainty. This keeps the doses of all the parts well within the regulatory limits (1500 - 5000 cGy) needed for safe and effective clinical irradiation. Dose calculation at any point (e.g., Point 9) = 2500 × 1.018 = 2545 cGy, with an acceptable tolerance of ±5%. **Conclusion:** Quality assurance tools for analyzing the doses provided throughout the canister in a linear accelerator to irradiation and radiation-sensitive indicator la-

bels offer visual validation of completed irradiation. It is recommended to perform irradiation as close as possible to the time of transfusion. This approach minimizes the storage duration after irradiation to the shortest possible number of days.

Keywords

Blood Irradiation, Linear Accelerator, Quality Assurance, TA-GVHD

1. Introduction

Transfusion-associated graft versus-host disease (TA-GVHD) is a serious immunological consequence of blood transfusion. TA-GVHD is an uncommon and typically fatal outcome resulting from blood products that contain lymphocytes, occurring in susceptible individuals following the transfusion of both whole blood and cellular products [1]. Patients with severe immunocompromised conditions are susceptible to TA-GVHD. This includes patients with cancer receiving chemotherapy or radiation therapy, as well as those with congenital immunodeficiencies and recipients of bone marrow transplants [2] [3]. Occasionally, it may develop in apparently immunocompetent patients.

TA-GVHD can occur in immunocompromised recipients (for example, newborns with congenital immunodeficiency disorders and bone marrow transplant recipients), but graft-versus-host disease has also been reported in immunocompetent transplant recipients. Fever and skin rash are the main symptoms of GVHD. The rash typically begins as a central erythematous, maculopapular response that spreads to the limbs and progresses to global erythroderma with bullae formation in severe cases. Other symptoms include anorexia, nausea, vomiting, and watery or bloody diarrhea [4]-[6]. TA-GVHD is a rare but severe complication typically found in immunosuppressed patients. As described by N.T.J. O'Connor *et al.* [7], a case involved an immunocompetent 77-year-old woman who developed the condition after receiving a single unit of blood from a donor with a homozygous HLA haplotype. The diagnosis should be suspected if aplastic anemia develops within 30 days of a transfusion. To prevent this, it is highly recommended that blood from first-degree relatives be irradiated to inhibit lymphocyte proliferation before use.

Irradiating blood and its constituent parts before transfusion is the only recognized way to avoid TA-GVHD. When exposed to ionizing radiation, T-lymphocytes lose their functional and proliferative capacities, whereas other blood components, including erythrocytes, granulocytes, and platelets, remain active and alive. T-lymphocytes are more radio-sensitive than other blood components, which makes this possible. To perform blood irradiation, specially constructed commercial irradiators exist, often placed in blood banks and dedicated entirely to this operation, and using a clinical linear accelerator [8].

Engrafted donor lymphocytes cause acute TA-GVHD, which is typically fatal. Dermatitis, high fever, hepatitis, severe gastrointestinal problems, and bone marrow suppression are all typical signs or symptoms. 2500 - 3000 cGy radiation does not significantly change lifetime or function of polymorphonuclear leukocytes or platelets. Irradiation reduces the viability of red blood cells (RBCs), and irradiated RBCs expire on the unit's typical expiration date or 28 days after irradiation, whichever comes first. Additionally, the extracellular fluid of stored erythrocytes accumulates potassium more quickly because of membrane damage. The irradiated blood units are not radioactive and do not require any extra care. Irradiated units can be reassigned to recipients other than the intended recipients [9]. Treatment is typically ineffective, whereas prevention, mainly via irradiation of blood components given to susceptible recipients, is the key to avoiding TA-GVHD [10] [11].

Instead of relying on dedicated equipment, we established a cost-effective internal blood irradiation service using existing linear accelerators (LINACs) of the Regina Elena Institute's (IRE). By integrating specific protocols and quality assurance measures, we successfully leveraged internal resources without disrupting workflows. This approach is safe and feasible and significantly reduces time and expenses, proving more advantageous than external alternatives [12]. Cellular blood component irradiation is a specialized technology used to reduce one of the most unusual but significant side effects of transfusion treatment or transplantation: transfusion-associated graft versus host disease (TA-GVHD). It is performed using x-rays or gamma-rays obtained from radioactive sources. Several affluent countries, including Japan, Australia, Canada, the United Kingdom, and New Zealand, have regulations and procedures for the transfusion of irradiated cellular blood components. To explain the various types of irradiators and irradiation processes, dosimetry methods, biochemical impact of irradiation on blood components, and role of blood component irradiation in TA-GVHD prevention. It will be important for clinicians to examine the most likely candidates for using irradiation blood components, considering their potential benefits [13]. Two forms of irradiation, x-rays and γ rays, inactivate T-lymphocytes. Both can irradiate blood components. T-lymphocytes can be inactivated by both "γ" and x-rays at the same dose. The atomic nuclei of cobalt 60 (^{60}CO) or cesium 137 (^{137}Cs) are the source of gamma rays (γ rays). Free-standing blood bank irradiators are the most used machines for irradiating blood components. They use one of the two isotopes as an irradiating source. When electrons contact a metallic surface, they emit x-rays. Linear accelerators emit x-rays for radiotherapy and can also be used to irradiate blood components [8] [14]. A linear accelerator produced ionizing radiation, to irradiate blood components. To assess the quality of irradiation-packed red blood cells (PRBCs), this study aimed to determine if the facility's present technique is effective in inhibiting T-lymphocyte growth without harming blood components. The degree of hemolysis, potassium levels, and T-lymphocyte proliferation were evaluated and contrasted with non-irradiated blood bags. In a linear accelerator,

packed red blood cell bags were exposed to 25 Gy of radiation [15]. Although potassium levels increased in all groups, it was most obvious in irradiated RBCs, especially after 7 days of storage, with a linear increase in storage time. At an acceptable dose of 25 Gy, the radiation of packed red blood cells (PRBCs) using a linear accelerator is effective, restricting T-lymphocyte proliferation while retaining red cell viability [16] [17]. Irradiation reduces the shelf life of PRBCs from 42 to 28 days [18].

Awareness among doctors, proper counseling of patients and attendants before blood transfusion, and use of irradiated blood products are the most viable approaches for preventing TA-GVHD in CABG and other surgical or nonsurgical purposes of blood transfusion [19]. It is safe to irradiate the blood with x-rays produced by linear accelerators in radiotherapy departments; however, according to the current level of scientific understanding, the authors suggest utilizing x-ray photon beam energy of 6 MV or less to avoid induced radioactivity in transfusion blood [20]. As established by J. M. Wahabi *et al.*, blood irradiation can be improved by using a custom acrylic box and build-up material to reduce Transfusion-Associated Graft versus Host Disease (TA-GvHD). Their method achieved high dose homogeneity (95% - 107%) and significantly streamlined the workflow, reducing irradiation time to 20 minutes for eight units [21]. According to H. TERZİ *et al.*, while blood transfusions can save lives, they can also produce serious side effects. A study of over 5000 patients found that irradiating erythrocyte and platelet products at dosages of 25 - 30 Gy effectively avoids the highly deadly Transfusion-Associated Graft Versus Host Disease (TA-GvHD) [22]. S. Shastry *et al.*, the study demonstrates that implementing a blood irradiation program using a linear accelerator and a custom acrylic box is a practical, accurate, and cost-effective alternative to dedicated, high-cost devices in resource-limited settings, delivering a 25 Gy dose using an Elekta Precise LINAC. The irradiation process was completed in less than 30 minutes. Validation of the radiation dose done using TLD showed less than ±3% variation. The blood component irradiation is within the scope of most of the hospitals in developing countries even in the absence of dedicated blood irradiators at affordable cost [23]. J. Naghinezhad *et al.*, showed that the use of linear accelerators (LINAC) as a practical substitute for commercial X-ray or gamma-irradiators for preventing post-transfusion GVHD has been validated by recent research. A key study demonstrated that a LINAC-based system delivering 30 Gy to platelet concentrates effectively suppressed T-cell proliferation and $CD8^+$ T-lymphocyte activity through G2 cell-cycle arrest. Importantly, this method maintained platelet quality without significantly affecting P-selectin expression or PAC-1 binding, proving it as a safe and cost-effective solution for centers lacking dedicated equipment [24]. The quality control of irradiated blood components should significantly improve our understanding of radiation's effects on cellular blood elements at the basic research level and in clinical practice. The widespread use of simple, convenient, and accurate dosimetry techniques will result in a safer and more viable component, as well as a better

knowledge of the relationship between dose and TA-GvHD prevention. M. E. Masterson and R. Febo [25], describe a technical procedure for the calibration of blood irradiators, including the determination of absolute dose rate and relative dose distribution. Results indicate differences of +5% to −13% with manufacturer-supplied calibrations and variations in the relative dose rate from 70% to 180%. The study discusses the clinical implications and the need for accurate dosimetry and quality assurance protocols.

2. Materials and Methods

To establish a new internal blood component irradiation service at Saudi German Hospital, we implemented standardized clinical protocols and comprehensive quality assurance programs using the Oncology Department linear accelerator (Varian CL2100CD) as a high-precision alternative to standalone irradiation devices, such as cobalt 60 (^{60}CO) or cesium 137 (^{137}Cs). Using our on-site Varian CL2100CD ensures safe and reliable blood irradiation within our facility.

2.1. Linear Accelerator, Varian

The linear accelerator Varian (Varian CL2100CD; Varian Medical Systems) is a high-energy machine that produces two kinds of energy: photon beam energies (6 and 15 MV) and five electron energies (4, 6, 9, 12, and 15 MeV). This study is located at Saudi German Hospital-Aseer. Linear accelerators used high-frequency electromagnetic waves to accelerate electrons (charged particles) to high energy (mega-electron volts) using a linear waveguide tube [26]. The accelerated electrons must impact a target with a high atomic number (tungsten), and the resulting high-energy X-rays can penetrate the body and interact with cancer cells [27]. The linear accelerator is calibrated to a dose of 1 cGy absorbed dose to water per monitor unit (MU), at a depth of maximum dose on the central axis and a field size of 10×10 cm^2.

2.2. Simulated Blood Unit Configurations and Irradiation Geometry

To evaluate the dosimetric accuracy of the blood component irradiation protocol, a controlled experimental study was conducted using simulated blood units.

Bag Contents and Volume: The evaluation used standard blood component bags filled with distilled water (450 mL each) to properly imitate the radiological density and volume of a standard packed red blood cell (PRBC) unit.

Samples and Measurements: A total of two independent simulated blood bags were evaluated. Point-dose measurements were acquired across nine distinct reference points (including the central core and eight peripheral zones) using a calibrated 0.6 cc Farmer ionization chamber to map spatial dose distribution. To ensure statistical reliability and minimize random experimental errors, point-dose measurements at each of the nine reference points were performed in triplicate for each simulated bag, and the mean values were utilized for dosimetric analysis.

Positioning and Setup: The simulated blood bag was arranged in a stationary, flat position on the treatment couch. To establish electronic equilibrium and ensure uniform backscatter, the bag was sandwiched between a 1 cm thick tissue-equivalent bolus on top (closer to the radiation source) and a 1 cm thick Perspex (acrylic) slab directly underneath.

Irradiation Technique Verified: Dosimetric verification was explicitly performed for the Direct Field Technique (single anterior field at a gantry angle of 0˚) targeting a prescribed central absorbed dose of 2500 cGy, delivered at a source-to-surface distance (SSD) of 100 cm and a field size of 30 × 30 cm^2.

The measurements in this work were performed using a high-energy linear accelerator (Varian CL2100CD; Varian Medical Systems), only using energy 6 MV photon beams, at our department, the configuration of a linear accelerator as shown in Figure 1.

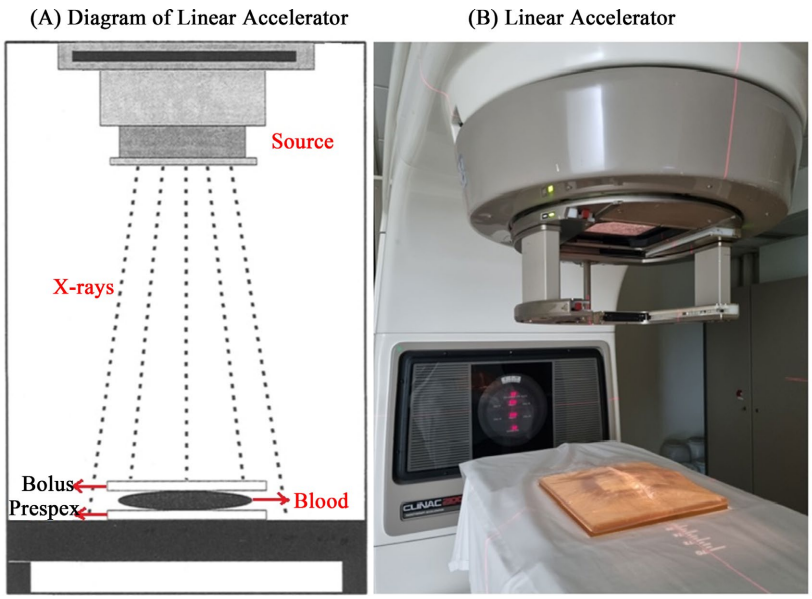


Figure 1. (A) Diagram of the device used for blood irradiation. (B) Linear accelerator (VARIAN Linac-CL2100 CD) used for blood irradiation.

A linear accelerator generates an x-ray beam over a specific dimension. The field is usually projected onto a table on top of a structure. The blood component is sandwiched between a 1 cm thick sheet of Perspex Slab, and the bolus on the top of the blood components (*i.e.*, closer to the radiation source) ensures electrical equilibrium of the secondary electrons as they pass through the blood component. The Perspex sheet at the bottom of the blood component allows for irradiation backscattering, aiding in the homogeneous delivery of x-rays beam. The blood components are kept stationary while the full x-ray dose is administered. Alternatively, instead of flipping the blood bag, the LINAC gantry can be rotated to deliver the remaining portion of the dose from an opposing angle. This procedure involves pausing the irradiation, rotating the gantry, and then restarting the accelerator to complete the irradiation.

2.3. Quality Assurance for Linear Accelerator

The linear accelerator should be warmed up before use. A variation of less than 3% is preferred for dosimetric outputs with the proper ion chamber. If any of these parameters are out of tolerance, the medical physicists are notified, and the linear accelerator clinical operation is halted until the problem has been investigated. The ODI is also checked at SSD = 100 cm, with a 2 mm tolerance.

2.4. Indicators of X-Ray Blood Irradiation

The blood irradiation indicator (Rad-Sure™ XR) enables clear visual verification of irradiation at the minimum prescribed dose **Figure 2**. These indications provide positive visual verification of the irradiation process. Rad-Sure™ XR has been the standard for blood irradiation indicators for over 25 years. It is made with Gafchromic™ film, the best resolution dosimeter in the world. Before irradiation, the label of the blood product reads "NOT IRRADIATED"; Post-irradiation, the word "NOT" is hidden and the indicator reads "IRRADIATED". **Benefits**: It is objective; when the film turns black and the word "NOT" is completely obscured, the product has been properly irradiated. The indicator's design is color-blind friendly, relying on text readability to confirm blood product irradiation. The system uses high-precision film technology, consistent with the global radiation oncology standards. Uses a powerful adhesive to assist the indicator to cling and stay on blood bags; it is straightforward to use: simply peel, stick, irradiate, and read. The U.S. FDA recognized the indicator; minimum doses of 15 Gy or 25 Gy are available [28].

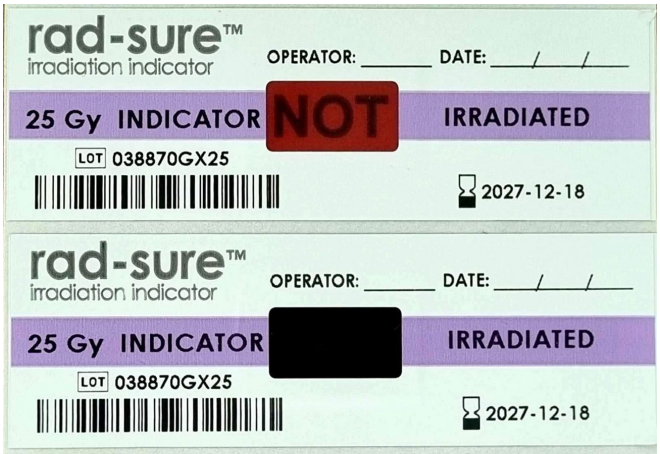


Figure 2. The Rad-Sure™ XR blood irradiation indicator before and after irradiation.

All blood components that might include viable T-lymphocytes should be irradiated for patients at risk of TA-GVHD. Whole blood units and cellular components (platelets, granulocytes, and red blood cells) that can be produced via aphaeresis or from whole blood. All types of red blood cells should be irradiated, whether they are suspended in citrated plasma or an additive solution [29] [30]. It is also important to irradiate the filtered red cell products. Furthermore, re-

searchers suggest that the T-lymphocyte load required to cause GVHD may depend on the patient's immunocompetence at the time of transfusion. The higher the level of immunosuppression, the fewer viable T-lymphocytes required to cause GVHD in vulnerable patients [31].

2.5. Evaluation of Lymphocyte Inactivation and Dose Specifications

According to the research, the PRBC and platelet components were irradiated in plastic containers at increasing radiation doses. Following each dose, samples were collected and the clonogenic proliferation of T-lymphocytes was determined using a restricted dilution approach. With PRBC units, 500 cGy had no effect, whereas 1500 cGy reduced T-lymphocyte proliferation by approximately 4 logs; however, considerable growth was still detected in both trials. Increasing the dose to 2000 cGy resulted in no T-lymphocyte proliferation in all but one experiment. No growth was observed after 2500 cGy. The FDA recommends delivering 2500 cGy to the internal mid-plane of a free-standing irradiation instrument canister while maintaining a minimum of 1500 cGy in all other areas within the canister [8] [32] [33].

2.6. Quality Assurance Measures

Verifying that blood components have been exposed to radiation and recording that the irradiation device is operating appropriately are necessary. For free-standing irradiators and linear accelerators, specific protocols are recommended to guarantee the proper execution of the irradiation process; they are listed in **Table 1**.

Table 1. Quality assurance for linear accelerator.

Measure	Time Interval
Absolute output calibration (Water phantom)	Annually
Mapping the dose iss (Blood bag simulation)	Quarterly
Beam quality uniformity	Quarterly
Consistency of the radiation field having an size	Periodically
Qualitative indicatlabel	For each component

Dose mapping evaluates radiation distribution within a simulated blood component. This applies to the irradiation field, where a linear accelerator is used as an irradiator. Dose mapping is essential for ensuring that irradiation treatments, such as blood irradiation, are delivered appropriately. It verifies that the appropriate irradiation dose is being administered at a defined position (for example, the center mid-plane of a canister) and specifies how the provided irradiation dose varies inside a simulated component or over a specified area. This allows us to draw conclusions on the highest and lowest doses delivered. Dose mapping should

be performed using sensitive dosimetry methods. To achieve consistent delivery using linear accelerators, the x-ray beam properties must be measured. Confirmation of blood component irradiation represents an important component of the quality assurance (QA) program.

2.7. Dose Mapping with Linear Accelerator

To ensure the accuracy of the radiation treatment, the linear accelerator is precisely monitored for the correct target dose delivery. Control methods, particularly those for determining the delivered dose to blood components, are essential for ensuring that linear accelerators function effectively for blood irradiation. The experimental setup utilized a standard blood bag filled with distilled water to simulate a blood unit and used an ion chamber (Farmer type chamber 0.6 cc TM30013). The source-to-surface distance (SSD) was set consistently to 100 cm referenced directly to the top surface of the 1 cm buildup bolus. Relative to this single SSD reference, the mid-plane core of the 1.0 cm thick blood bag corresponds to a physical depth of 1.5 cm, while the ionization chamber was positioned immediately beneath the bag at a total depth of 2.0 cm (sandwiched between the bag's bottom surface and the underlying 1 cm Perspex backscatter slab). Consequently, the point-dose measurements acquired at the nine designated points represent the exit-dose profile at the bottom region of the blood component, as shown in Figure 3. The irradiation was performed using a 30 × 30 cm^2 field size, delivering 100 MU with 6 MV photon beam energy. When the accelerator is turned on, the absolute dose was measured using a UNIDOS webline electrometer (TM41047, PTW Freiburg), and the reading was recorded. Subsequently, each point reading was divided by the reading at the center of the field to determine the percentage of the dose delivered at that specific point. This value was multiplied by the total irradiation dose. Comparative studies using such simulated

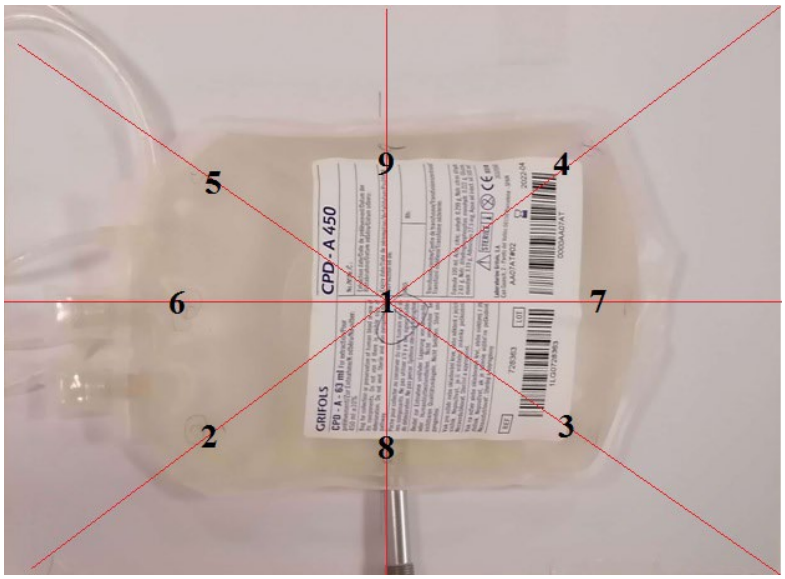


Figure 3. Picture of blood bag under a linear accelerator with the measured point.

blood units revealed a more uniform radiation delivery with linear accelerators, reflecting the relative homogeneity of x-ray beams.

Blood irradiation involves exposing blood to a minimum radiation of typically 25 Gy (the ionizing radiation measurement unit is represented by Gray [Gy]). Radiation is modification of blood products; it prevents lymphocytes from reproducing while leaving the blood cells virtually unharmed. Blood that has been irradiated and blood components must be prepared using methods verified to ensure that irradiation occurs. A method must be used to indicate that irradiation occurred for each batch.

2.8. Three Blood Irradiation Techniques

Radiation protocols for linear accelerators are adjusted based on the distance between the blood or platelet units and the radiation source, the number of bags being treated, and the required dose delivery range [34]. Optimal irradiation ensures a homogeneous dose distribution within the bags, thus effectively inhibiting T-lymphocyte proliferation [35]. In the Oncology Department of the Saudi German Hospital, the hospital's blood bank produces PRBCs or platelet units, which are then irradiated using a linear accelerator (Varian CL2100CD) with a photon energy of only 6 MV. This study evaluates radiation dosimetry in blood components to verify the efficacy of linear accelerators as a substitute for conventional irradiators. The goal of the study is to ensure high-quality irradiation standards using LINAC technology. Three established methods for blood irradiation:

1) Direct field: for irradiating one or two bags of blood RBCs, the dose is equal to 2500 cGy, as shown in **Table 2**.

2) Parallel opposed fields: anterior and posterior (AP) and posterior and anterior (PA), used for more bags than 4 bags; each AP and PA field dose equals 1250 cGy.

3) Four-field (box technique): (opposing AP and 2 lateral fields opposed) in irradiating the blood, used for more than 10 bags, each field equal dose of 625 cGy.

Perform blood component irradiation and document:

a) Place the Perspex sheet 1 cm under the blood.

b) Open the field size to 30×30 cm^2.

c) Add the bolus 1cm on the blood or platelet bag surface; calculate the dose at depth 1.5 cm using the photon energy of 6 MV.

d) The surface source distance (SSD) from the bolus SSD = 100 cm.

e) Used the dose at separate time continuously equal to 2500 cGy.

2.9. Verification of Absolute Dose and Traceability of Calibration

To independently confirm the delivery of the prescribed absolute absorbed dose of 2500 cGy at the central reference point (rather than relying solely on normalized relative values), a strict calibration traceability chain was maintained. The absolute output of the Varian CL2100CD linear accelerator was calibrated to water following the international IAEA-TRS 398 dosimetry protocol. For the specific

Table 2. Treatment protocol, varian linac-Cl2100 CD blood irradiation and dose prescription.

ID Patient: Patient Name:	
Number of Field	One Direct Field
Gantry angle (˚)	0˚
Collimator angle (˚)	0˚
Couch angle (˚)	0˚
Energy	6 MV
Total Dose	2500 cGy
No. of Fractions	1
Field size (Collimator) (L × W) (cm)	30 cm
Equivalent Square	30 cm
PDD%	99.3%
Output Correction Factor (OCF)	1.086
Bolus (cm)	1.0 cm
Surface to Skin Distance (SSD) (cm)	100
Prescribed Depth (d) (cm)	1.5 cm
Prescribed tumor dose	2500 cGy
Applied Monitor Unit (MU)	2318

direct field configuration (10 × 10 cm^2 field size at a 100 cm SSD reference surface), the absolute absorbed dose delivered to the reference position was verified using the calibrated Farmer ionization chamber and electrometer from KFSH&RC in Riyadh. The reference calculation directly incorporated the machine's absolute baseline calibration factor (N_w^{Co}), the measured temperature-pressure correction factor ($K_{T,P}$ = 1.261), and a standard Output Correction Factor (OCF = 1.000) for the reference 10 × 10 cm^2 field. To establish calibration traceability for the specific clinical blood irradiation setup (30 × 30 cm^2 field at an effective mid-plane depth of d = 1.5 cm), the absolute dose delivered per monitor unit was converted using the clinical percentage depth dose (PDD = 99.3%) and the measured field scatter output factor (OCF = 1.086 for the 30 × 30 cm^2 field), yielding an estimated compound measurement uncertainty of 3.2%.

3. Results and Discussion

3.1. Ensuring Linear Accelerator Precision

Quality assurance (QA) protocols were implemented for the 6 MV photon beam on a Varian CL2100CD linear accelerator. QA involves the mechanical and radiation tests. Mechanical check: the test was measured by the light field system and rangefinder calibration was checked. **Table 3** presents the tolerance values for

each parameter. The dosimetric outputs measured using appropriate ionization chambers should demonstrate a deviation below 3%. In the event of parameters exceeding tolerance levels, the clinical use of the linear accelerator is halted and subjected to recalibration by a medical physicist to verify dose accuracy. The optical distance indicator (ODI) is verified at SSD = 100 cm with 2 mm tolerance. The congruence between the light and radiation fields, along with the photon energy consistency, was evaluated. The measured values fell within the acceptance limits of the machine and demonstrated strong agreement with the published tolerance levels for comparable linear accelerators [36].

Table 3. Quality assurance checks for the Varian CL2100CD linear accelerator.

Check	Item	Part	Tolerance	Measured	Remarks
Mechanical checks					
The light field system	1	Light field and Cross hairs	±2 mm	9.99 × 10 cm^2 30.1 × 30 cm^2	10 × 10 cm^2, 0˚ 30 × 30 cm^2, 0˚
Rangefinder Calibration	1	Optical Distance Indicator (ODI)	±1 mm	0.8 mm	100 cm
Radiation checks					
Light versus radiation field congruence	1	Light fields and crosshairs	±2 mm	1.2 mm	30 × 30 cm^2, 0˚
Photon energy	1	Buildup depth	1.5 ± 0.2 cm	1.5	depth ionization curve
	2	Ionization percentage	66.5%	66.30%	10 × 10 cm^2 at depth 10 cm

3.2. The Absolute Output Dose

The doses for all photon energies in this study were calibrated to be 1 cGy per 1 MU at a corresponding d_{max} at SSD equal 100 cm for a photon field size 10 × 10 cm^2 which is defined as "standard dose output". The absolute output dose at field sizes from 10 × 10 cm^2 was measured using a 0.6 cc farmer-type ionization chamber in a Perspex slab phantom at SSD = 100 cm, depth = 10 cm, and 100 MU for 6 MV under the following conditions of temperature and pressure (Mu = 100, T = 20.5, P = 803.2 hpa), as shown in Table 4.

The Varian CL2100CD linear accelerator is calibrated using an ionization chamber, with the X-ray beam undergoing at least weekly verification to maintain optimal standards for blood component irradiation. The following parameters are monitored to validate the equipment's status before clinical use:

1) Source-to-surface distance (SSD);

2) Beam output consistency;

3) X-ray beam intensity.

The distance between the radiation source and the placement area of the blood component can be readily verified using a calibrated measuring device with an Optical Distance Indicator (ODI). The beam current is routinely monitored to ensure beam output consistency. Furthermore, the beam intensity is determined

Table 4. Measurement of the absolute output dose for 6 MV photon beam energy with 10 × 10 cm² field size at SSD = 100 cm and 100 MU.

CALIBRATION OF VARIAN Linac– CL2100CD
Measurement absorbed dose ***ONCOLOGY DEPARTMENT,***
Photons & Electrons beam, according to IAEA-398 Protocol ***MEDICAL PHYSICS UNIT***
Using UNIDOS electrometer (PTW), ion chamber (0.6 cc and Roos)

1- Set-up: Radiation source: **VARIAN Linac– CL2100CD**

Photons energy:(6 and 15) MV, Electron energy:(4, 6, 9, 12, and 16) MeV

d_{max}: 2.8cm (15MV),1.5cm (6MV),2.9cm (16MeV),2.3cm (12MeV),1.9cm (9MeV),1.3cm (6MeV) and 0.6cm (4MeV)

Gantry & Collimator angle=**0°** Field size = **10x10 cm²** , **Applicator = 10x10 cm²** SSD = **100 cm**

2- Dosimetry System: Dose =**100 MU**

Solid water phantom: RW3 slab phantom for all energy, UNIDOS electrometer (PTW) T10021-002226

0.6 cc (PTW) at 10 cm depth Photons energy:(6 and15) MV, 0.6 cc for 12 and 16 MeV at dmax.

N_w^{Co} (Calibration factor) = **5.408** cGy/nC, According to Calibration Certificate / **8-Apr-26**

Roos (PTW) ion chamber using at dmax for low energy:(4,6 & 9) MeV

N_w^{Co} (Calibration factor) = **8.397** cGy/nC, According to Calibration Certificate / **8-Apr-26**

$K_{Q\ 15MV}$ (Quality conversion factor) = **0.975** $K_{Q\ 6MV}$ = **0.991** K_{Q16MeV} = **0.904**

K_{Q12MeV} = **0.907** K_{Q9MeV} = **0.925** K_{Q6MeV} = **0.939** K_{Q4MeV} = **0.960**

$\%DD_{10cm}$ (Percentage Depth Dose at 10 cm depth)$_{6MV}$ **66.33**

$\%DD_{10cm}$ (Percentage Depth Dose at 10 cm depth)$_{15MV}$ **76.12**

K_{pol} is polarity effect = **1.000** K_{elect} is electrometer calibration factor= **1.000**

K_s is ion recombination correction factor = **1.000** water / solid ratio = **1.012**

K_h is humidity correction factor = **0.997**

3- Dose Calculation: $D_w = R \times N_W \times M$

$D_{w(MV)}$ (cGy)=R×[(273+T)/P(mbar)][(1013.25/293) × N_w^{co} × k_Q × k_{elec} × k_s × k_{pol} × k_h ×(100/PDDat10cm) × 1.012]

$D_{wdmax\,(MeV)}$ (cGy) = R x [(273 + T) / P (mbar)] [(1013.25/293) x N_w^{co} x k_Q x k_{elec} x k_s x k_{pol} x k_h x 1.012]

$K_{T.P}$ is Air density correction factor ; P_o = **1013.2 mbar** , T_o = **20 °C**,

$$K_{T.P} = \frac{(273.2+T)*P_0}{(273.2+T_0)*P} = \mathbf{1.261}$$

Measurements: Measured by: Ayman G. Ibrahim **Date: 25/06/2026**

T.(°C)	20		Pressure(mbar)			803.2
Reading	Energy					
	15 MV	6 MV	16 MeV	12 MeV	9 MeV	6 MeV	4 MeV
R_1	0.00	9.82	0.00	0.00	0.00	0.00	0.00
R_2	0.00	9.84	0.00	0.00	0.00	0.00	0.00
Corected Dose							
A. Dose	0.0	101.1	0.0	0.0	0.0	0.0	0.0

** By using the electrometr UNIDOS (PTW), 0.6 cc (PTW) ion chamber at 10 cm depth, and Roos (PTW) ion chamber at dmax for lower energy electron from 4 to 9 MeV, 0.6 cc for higher energy electron up to 10 MeV.

by detecting the ionization current within a monitoring ionization chamber array, which is expressed as the number of photons provided per square cm. These parameters must be routinely evaluated as part of the quality control protocol implemented by the medical physicist [37].

3.3. Confirmation of Irradiation Occurred and Dose Mapping

A radiation-sensitive indicator label is used to validate the results to ensure the irradiation process has occurred. When an indicator label is placed on the surface of the blood component bag and irradiated, a clear visual transformation occurs:

The label's film strip transforms from a clear red color to an opaque color, causing the word "NOT" to disappear, as illustrated in Figure 4. Two types of indicator labels are available: 1500 and 2500 cGy. These ratings estimate the absorbed radiation threshold required to change the window from transparent red to opaque, obscuring the word "NOT". Consequently, these Rad-Sure indicator labels serve strictly to provide a qualitative confirmation of radiation exposure, visually verifying that the unit underwent the process. They do not, however, measure the precise dose distribution. To establish independent compliance with the prescribed absolute target dose throughout the blood component volume and verify spatial uniformity, quantitative dosimetry using a calibrated ionization chamber remains mandatory.



Figure 4. The label on the blood bag (A) before irradiation and (B) after irradiation using a photon beam 6 MeV.

Linear accelerator Varian CL2100 CD, 6 MV, Field Size (30×30 cm^2), with SSD = 100 cm referenced strictly to the top surface of the 1 cm bolus. Under this configuration, point-dose assessments were mapped using a 0.6 cc ion chamber positioned at a depth of 2.0 cm, representing the base exit-dose region directly beneath the blood bag and above the 1 cm Perspex backscatter slab. Measurements are expressed in terms of absorbed dose using Gray (Gy) or centi-gray (cGy) units in dosimetry systems. While these measurements directly reflect the spatial dose uniformity across the bottom layer of the component volume, all dosimetric measurements are inherently subject to a degree of uncertainty. The degree of uncertainty depends on the type of dosimeter used. Dosimeters typically have a tolerance ±5% of the measured value. Table 5 shows reading the dose at various points on the blood bag by using a PTW electrometer and farmer ion chamber 0.6 CC.

For a prescribed central target dose of 2500 cGy, the absolute dose distribution across the bag volume was computed using the relative local uniformities mapped in Table 6. For the first measurement series, the localized dose extended from a minimum of 2545 cGy (at points 5 and 9, corresponding to a relative factor of

1.018) to a maximum of 2585 cGy (at point 6, with a relative factor of 1.034). Correspondingly, for the second measurement series, the distributed dose ranged from a minimum of 2465 cGy (at point 8, with a relative factor of 0.986) to a maximum of 2557.5 cGy (at point 6, with a relative factor of 1.023). The measured center-point dose complies with the 2500 cGy prescription, constrained strictly within the ±5% dosimetric measurement uncertainty (2375 - 2625 cGy). This ±5% range reflects the physical tolerance of the dosimetry system rather than a modification of clinical thresholds, ensuring the reference dose is accurately delivered to the core while maintaining clinical efficacy and component safety.

Table 5. Reading dose at a point on the blood bag using PTW electrometer and 0.6 CC ion chamber.

	Point (1) Center	Point (2)	Point (3)	Point (4)	Point (5)	Point (6)	Point (7)	Point (8)	Point (9)
1 Blood Bag	14.43	14.83	14.88	14.82	14.69	14.91	14.80	14.77	14.69
2 Blood Bag	13.50	13.64	13.56	13.44	13.33	13.80	13.56	13.30	13.60

Table 6. All data relative dose reading to the first point on the bag blood using PTW electrometer and 0.6 CC ion chamber.

	Point (1) Center	Point (2)	Point (3)	Point (4)	Point (5)	Point (6)	Point (7)	Point (8)	Point (9)
1 Blood Bag	1	1.03	1.03	1.027	1.018	1.034	1.026	1.024	1.018
2 Blood Bag	1	1.01	1.005	0.996	0.988	1.023	1.005	0.986	1.008

The same procedure should be used to determine the minimum value on a dose map. Furthermore, the actual minimum irradiation dosage map should not be less than 1500 cGy.

This calibration procedure utilizes a Linear Accelerator (Varian CL2100CD) and ion chamber (farmer type 0.6 cc) measurements to ensure that every corner of the blood bag receives a uniform and accurate dose. By verifying that doses remain within the ±5% tolerance (targeting 2500 cGy and maintaining a minimum above 1500 cGy), this process effectively inactivates T-lymphocytes to prevent their proliferating. This stringent quality control is essential to mitigate the risk of TA-GVHD, guaranteeing safe and effective transfusions for immunocompromised patients.

The Nuclear and Radiological Regulatory Commission of Saudi Arabia has formally approved the linear accelerator as a validated replacement for the compact gamma-ray irradiator previously recommended for blood component irradiation. Regardless of the method used, the procedure validation is the most critical factor. The recommended radiation dose is 25 Gy (2500 cGy), which is considered adequate for lymphocyte inactivation. The dose must be maintained within a specific range: it should not fall below 15 Gy, as this fails to inhibit lymphocyte proliferation, nor should it exceed 50 Gy, due to the risk of serious red blood cell damage. While lymphocyte inactivation and the preservation of cellular blood-

component quality were not biologically assayed within this study's framework, extensive cited medical literature demonstrates that achieving these verified dosimetric ranges results in a substantial reduction in lymphocyte proliferation. Consequently, as established by global findings, providing concrete evidence that an effective absolute radiation dosage has been supplied successfully confirms the efficiency of this protocol, thereby significantly mitigating the clinical risk of TA-GVHD in vulnerable transfusion recipients. Additionally, while linear accelerators are known worldwide to be more cost-effective than standalone blood irradiators, a specific economic analysis was not performed in our local hospital setup. According to research published by M. J. Butson *et al.*, [38] radiochromic film is an ideal dosimeter for verifying blood irradiation doses. Their study confirmed that film measurements matched ionization chamber results within ±6% (at a 95% confidence limit), ensuring that the applied dose remains within the safe range of 29.5 - 31.7 Gy to prevent TA-GVHD. According to the findings of T. Cheung *et al.*, [39] the diode detector measured blood irradiation doses within a 5.4% accuracy range, delivering doses in a dual-field setup with a 6 MV photon beam on a linear accelerator. Their research highlights that the compaction of scattering materials often causes unintended dose reductions. They recommend using diode detectors for instant data and a film dosimeter, such as radiochromic film, for visual confirmation to assure precision.

4. Conclusion

Comprehensive absolute calibration of the linear accelerator is performed annually using an ionization chamber and a water phantom to ensure x-ray output consistency. In contrast, specific blood dose mapping and relative uniformity profiles are verified quarterly as outlined in the quality assurance protocols to maintain clinical safety. The radiation process using a clinical linear accelerator (Varian CL2100CD) is effective for delivering the required baseline physical dosage (2500 cGy at the center of the field and a minimum of 1500 cGy elsewhere). According to cited clinical literature, satisfying these strict volumetric dose limits is known to successfully inhibit T-lymphocyte multiplication while preserving the viability of RBCs intended for transfusion. Irradiated RBCs can be stored for 28 days after being irradiated or until their initial expiry date, whichever occurs first. Given the growing use of linear accelerators to irradiate blood components, proper quality assurance procedures must be implemented. Consequently, dosimetric verification of blood component irradiation protocols demonstrates that a clinical linear accelerator (LINAC) provides a highly precise and compliant means of radiation delivery, where common tolerances for dose variation typically fall within ±5%. While local economic cost-effectiveness was not formally assessed, the clinical implementation of this service leverages existing on-site radiotherapy hardware under rigorous quality assurance protocols to maintain regulatory compliance. Finally, irradiation should be performed as close to the time of transfusion as possible, ideally within the first 7 days, to minimize the post-irradiation storage du-

ration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Foukaneli, T., Kerr, P., Bolton-Maggs, P.H.B., Cardigan, R., Coles, A., Gennery, A., *et al.* (2020) Guidelines on the Use of Irradiated Blood Components. *British Journal of Haematology*, **191**, 704-724. https://doi.org/10.1111/bjh.17015

[2] Góes, E.G., Borges, J.C., Covas, D.T., Orellana, M.D., Palma, P.V.B., Morais, F.R., *et al.* (2005) Quality Control of Blood Irradiation: Determination T Cells Radiosensitivity to Cobalt-60 Gamma Rays. *Transfusion*, **46**, 34-40. https://doi.org/10.1111/j.1537-2995.2005.00669.x

[3] Treleaven, J., Gennery, A., Marsh, J., Norfolk, D., Page, L., Parker, A., *et al.* (2010) Guidelines on the Use of Irradiated Blood Components Prepared by the British Committee for Standards in Haematology Blood Transfusion Task Force. *British Journal of Haematology*, **152**, 35-51. https://doi.org/10.1111/j.1365-2141.2010.08444.x

[4] Ahya, R., Douglas, J.G. and Watson, H.G. (1998) Transfusion Associated Graft versus Host Disease in an Immunocompetent Individual Following Coronary Artery Bypass Grafting. *Heart*, **80**, 299-300.

[5] Rühl, H., Bein, G. and Sachs, U.J.H. (2009) Transfusion-Associated Graft-Versus-Host Disease. *Transfusion Medicine Reviews*, **23**, 62-71. https://doi.org/10.1016/j.tmrv.2008.09.006

[6] Sunul, H. and Erguven, N. (2013) Transfusion-Associated Graft-Versus-Host Disease. *Transfusion and Apheresis Science*, **49**, 331-333. https://doi.org/10.1016/j.transci.2013.07.001

[7] O'Connor, N.T. and Mackintosh, P. (1992) Transfusion Associated Graft versus Host Disease in an Immunocompetent Patient. *Journal of Clinical Pathology*, **45**, 621-622. https://doi.org/10.1136/jcp.45.7.621

[8] Moroff, G. and Luban, N.L.C. (1997) The Irradiation of Blood and Blood Components to Prevent Graft-Versus-Host Disease: Technical Issues and Guidelines. *Transfusion Medicine Reviews*, **11**, 15-26. https://doi.org/10.1016/s0887-7963(97)80006-5

[9] New York State Council on Human Blood and Transfusion Services (2012) New York State Council on Human Blood and Transfusion Services Guidelines for Irradiation of Blood and Blood Components. Fourth Edition, New York State Council on Human Blood and Transfusion Services.

[10] Dwyre, D.M. and Holland, P.V. (2008) Transfusion-Associated Graft-versus-Host Disease. *Vox Sanguinis*, **95**, 85-93. https://doi.org/10.1111/j.1423-0410.2008.01073.x

[11] Przepiorka, D., Leparc, G.F., Stovall, M.A., Werch, J. and Lichtiger, B. (1996) Use of Irradiated Blood Components: *Practice Parameter. American Journal of Clinical Pathology*, **106**, 6-11. https://doi.org/10.1093/ajcp/106.1.6

[12] Pinnarò, P., Soriani, A., D'Alessio, D., Giordano, C., Foddai, M.L., Pinzi, V., *et al.* (2011) Implementation of a New Cost Efficacy Method for Blood Irradiation Using a Non Dedicated Device. *Journal of Experimental & Clinical Cancer Research*, **30**, Article No. 7. https://doi.org/10.1186/1756-9966-30-7

[13] Bodade, A., Kumar, I.S.C. and Manii, A. (2024) Irradiation of Blood Components in

Combating Transfusion Associated Graft versus Host Disease (TA-GvHD). *Medicine India*, **3**, 8-20. https://doi.org/10.25259/medindia_35_2023

[14] Sampathrajan, S., Govindaraj, K., Nandagopal, A. and Shanmugam, S. (2025) Clinical Implementation and Validation of a New Indigenously Designed Cost-Effective Blood Irradiation Phantom Box for Use with Linear Accelerator. *Annals of Oncology Research and Therapy*, **5**, 128-134. https://doi.org/10.4103/aort.aort_5_25

[15] Balasubramanyam, P., Basavarajegowda, A., Hanumanthappa, N., Negi, V.S. and Harichandrakumar, K.T. (2021) Irradiating Stored Blood and Storing Irradiated Blood: Is It Different? A Study of Serial Changes in Biochemical Parameters of Red Blood Cell Units. *Asian Journal of Transfusion Science*, **15**, 172-178. https://doi.org/10.4103/ajts.ajts_71_21

[16] Olivo, R.A., da Silva, M.V., Garcia, F.B., Soares, S., Rodrigues Junior, V. and Moraes-Souza, H. (2015) Evaluation of the Effectiveness of Packed Red Blood Cell Irradiation by a Linear Accelerator. *Revista Brasileira de Hematologia e Hemoterapia*, **37**, 153-159. https://doi.org/10.1016/j.bjhh.2015.03.001

[17] Suzuki, Y., Tateishi, N., Cicha, I., *et al.* (2000) Decreased Deformability of the X-Ray-Irradiated Red Blood Cells Stored in Mannitol-Adenine-Phosphate Medium. *Clinical Hemorheology and Microcirculation*, **22**, 131-141.

[18] Xu, D., Peng, M., Zhang, Z., *et al.* (2012) Study of Damage to Red Blood Cells Exposed to Different Doses of γ-Ray Irradiation. *Blood Transfusion*, **10**, 321-330.

[19] Saba, S., Tabassum, N., Kamal, M., Khalequzzaman, Islam, M.M. and Billah, M.M. (2024) Transfusion-Associated Graft vs Host Disease in a Post-Coronary Artery By-pass Graft Patient. *Journal of Medical Health Research and Psychiatry*, **1**, 1-3. https://doi.org/10.70844/jmhrp.2024.1.2.22

[20] Frentzel, K. and Badakhshi, H. (2016) Irradiation with X-Rays of the Energy 18 MV Induces Radioactivity in Transfusion Blood: Proposal of a Safe Method Using 6 Mv. *Medical Physics*, **43**, 6517-6524. https://doi.org/10.1118/1.4967482

[21] Wahabi, J.M., Abu Hanifah, N.Z.H., Hashim, S. and Bradley, D.A. (2022) Modified Irradiation Technique for Transfusable Blood Using a Clinical Linear Accelerator. *Radiation Physics and Chemistry*, **200**, Article 110277. https://doi.org/10.1016/j.radphyschem.2022.110277

[22] Terzi, H., Inanir, M., Yilmaz, H., Yurtsever, İ. and Şencan, M. (2023) Evaluation of Possible Complications of Irradiation of Blood Products on Patients. *Cumhuriyet Medical Journal*, **45**, 7-12. https://doi.org/10.7197/cmj.1310755

[23] Shastry, S., Ramya, B., Ninan, J., Srinidhi, G.C., Bhat, S.S. and Fernandes, D.J. (2013) Linear Accelerator: A Reproducible, Efficacious and Cost Effective Alternative for Blood Irradiation. *Transfusion and Apheresis Science*, **49**, 528-532. https://doi.org/10.1016/j.transci.2013.03.007

[24] Naghinezhad, J., Hosseini, E., Siavashpour, Z., Houshyari, M., Khajetash, B. and Ghasemzadeh, M. (2024) Designing a Linear Accelerator-Based "X Irradiation System" for Platelet Products: An Efficient, Safe, Accessible and Cost-Effective Alternative for Conventional X- or Gamma Irradiators. *Scientific Reports*, **14**, Article No. 28363. https://doi.org/10.1038/s41598-024-80118-6

[25] Masterson, M.E. and Febo, R. (1992) Pretransfusion Blood Irradiation: Clinical Rationale and Dosimetric Considerations. *Medical Physics*, **19**, 649-657. https://doi.org/10.1118/1.596809

[26] Podgorsak, E.B. (2005) Treatment Machines for External Beam Radiotherapy. *Radiation ONCOLOGY Physics: A Handbook for Teachers and Students*, International

Atomic Energy Agency, 123-160.

[27] Khan, F.M. (2010) The Physics of Radiation Therapy. Lippincott Williams & Wilkins.

[28] https://www.ashland.com/industries/medical/blood-safety/rad-sure-bood-irradiation-indicators

[29] Suda, B.A., Leitman, S.F. and Davey, R.J. (1993) Characteristics of Red Cells Irradiated and Subsequently Frozen for Long-Term Storage. *Transfusion*, **33**, 389-392. https://doi.org/10.1046/j.1537-2995.1993.33593255598.x

[30] Miraglia, C.C., Anderson, G. and Mintz, P.D. (1994) Effect of Freezing on the *in Vivo* Recovery of Irradiated Red Cells. *Transfusion*, **34**, 775-778. https://doi.org/10.1046/j.1537-2995.1994.34994378278.x

[31] Linden, J.V. and Pisciotta, P.T. (1992) Transfusion-Associated Graft-Versus-Host Disease and Blood Irradiation. *Transfusion Medicine Reviews*, **6**, 116-123. https://doi.org/10.1016/s0887-7963(92)70161-8

[32] Pelszynski, M., Moroff, G., Luban, N., Taylor, B. and Quinones, R. (1994) Effect of Gamma Irradiation of Red Blood Cell Units on T-Cell Inactivation as Assessed by Limiting Dilution Analysis: Implications for Preventing Transfusion-Associated Graft-Versus-Host Disease. *Blood*, **83**, 1683-1689. https://doi.org/10.1182/blood.v83.6.1683.1683

[33] Leitman, S.F. (1993) Dose, Dosimetry, and Quality Improvement of Irradiated Blood Components. *Transfusion*, **33**, 447-449. https://doi.org/10.1046/j.1537-2995.1993.33693296804.x

[34] Patton, G.A. and Skowronski, M.G. (2001) Implementation of a Blood Irradiation Program at a Community Cancer Center. *Transfusion*, **41**, 1610-1616. https://doi.org/10.1046/j.1537-2995.2001.41121610.x

[35] EDQM (2025) BLOOD COMPONENTS European Committee on Blood Transfusion (Partial Agreement) (CD-P-TS).

[36] Smith, K., Balter, P., Duhon, J., White, G.A., Vassy, D.L., Miller, R.A., *et al.* (2017) AAPM Medical Physics Practice Guideline 8.a.: Linear Accelerator Performance Tests. *Journal of Applied Clinical Medical Physics*, **18**, 23-39. https://doi.org/10.1002/acm2.12080

[37] Nath, R., Biggs, P.J., Bova, F.J., Ling, C.C., Purdy, J.A., van de Geijn, J., *et al.* (1994) AAPM Code of Practice for Radiotherapy Accelerators: Report of AAPM Radiation Therapy Task Group No. 45. *Medical Physics*, **21**, 1093-1121. https://doi.org/10.1118/1.597398

[38] Butson, M.J., Yu, P.K.N., Cheung, T., *et al.* (1999) Dosimetry of Blood Irradiation with Radiochromic Film. *Transfusion Medicine*, **9**, 205-208. https://doi.org/10.1046/j.1365-3148.1999.00200.x

[39] Cheung, T., Butson, M. and Yu, P.K.N. (2001) Validation of Blood Product Irradiation Doses. *Physics in Medicine and Biology*, **46**, N241-N244. https://doi.org/10.1088/0031-9155/46/10/402

Abbreviations

TA-GVHD	Transfusion Associated-Graft Versus Host Disease
QA	Quality Assurance
MV	megavolt
PRBCs	packed red blood cells
RBC	red blood cell
Linac	linear accelerator
γ rays	Gamma rays
^{60}CO	cobalt 60
^{137}Cs	cesium 137
CU	calibration units
MU	monitor unit
6MV	6 megavoltage
Gy	Gray
cGy	centigray
CABG	Coronary Artery Bypass Graft
U.S. FDA	United States Food and Drug Administration
Rad-Sure™ XR	blood irradiation indicator label
SSD	Source-to-Skin Distance
0.6 cc	Farmer chamber (0.6 cubic centimetre)
PTW	Physikalisch-Technische Werkstätten (PTW Freiburg GmbH is a German)
ODI	Optical Distance Indicator
SGH	Saudi German Hospital
AP	Anterior and posterior
PA	posterior and Anterior
box technique	four-field box or 4FB technique
KFSH&RC	King Faisal Specialist Hospital and Research Centre
K^+	Potassium ion
T	temperature
P	pressure
mmol/L	millimoles per liter
mEq/L	milliequivalents per liter
NRRC	Nuclear and Radiological Regulatory Commission