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Assessment of Leakage Radiation and Radiobiological Impacts in Gamma Knife Radiosurgery: Dosimetric and Biological Analysis

Bazhdar N. Mohammed[1†], Asaad H. Ismail[1] and Edrees M. Tahir[1,2]

[1]Department of Physics, College of Education, Salahaddin University-Erbil, Erbil, Kurdistan Region – F.R. Iraq

[2]Department of Medical Technical Radiology, Erbil Technical Health and Medical College, Erbil Polytechnic University, Erbil, Kurdistan Region – F.R. Iraq

***Abstract*—Gamma Knife radiosurgery is a non-invasive radiotherapy technique for brain lesions. However, radiation leakage from collimators and high-dose exposure may alter blood parameters, potentially increasing the risk of secondary cancers and other complications. The purpose of this study is to measure the leakage radiation produced during trigeminal neuralgia and meningiomas lesion treatments and impact on various radiosensitive organs. In addition, the radiobiological impact on patients' blood parameters is investigated for both short-term and long-term treatment exposure. Scatter radiation was measured using dosimeters placed at various body regions. Blood samples were collected from 20 patients at three different times. Changes in parameters were statistically analyzed using one-way analysis of variance, to assess significant differences across the time points. The highest scatter radiation levels were recorded at the face and neck significantly exceeding other body regions about 110 µSv and 350 µSv, respectively. Statistical analysis revealed that long-term exposure (58.2 min at 80 Gy) in trigeminal neuralgia cases resulted in significantly greater blood parameter changes ($p \leq 0.05$) compared to short-term exposure (19.4 min at 20 Gy) in meningiomas. These findings reveal dose-dependent blood changes and highlight the importance of radiation protection measures to enhance patient safety, particularly during high-dose treatments.**

***Index Terms*—Gamma knife radiosurgery, Leakage radiation, Patient Safety, Radiation dose, Radiobiological impacts.**

I. Introduction

Gamma Knife radiosurgery (GKRS) is a non-invasive procedure that administers accurate, high-dose radiation to specific areas of the brain, making it an effective treatment for a range of neurological conditions, such as brain tumors, vascular malformations, and functional disorders (Stone, et al., 2025). It utilizes multiple cobalt-60 (^{60}Co) sources that converge at a single focal point, using an internal collimator to direct the photon beams generated by the decay of ^{60}Co toward the tumor or abnormality. The system contains 192 sources, distributed across 8 sectors, with each sector holding approximately 24 capsules, each with an activity of 3,000 curies from the date of neutron activation (Ismail et al., 2025). The amount of the prescribed dose during GKRS planning depends on the type of lesion being treated, as different lesions require different dosages to achieve optimal therapeutic effects, such as trigeminal patients, one of the highest suggested dosages for GKRS treatments is 85–85 Gy (Verheul, et al., 2010; Barzaghi, et al., 2021). Meanwhile, certain cases, such as meningiomas, often require lower doses of radiation, typically around 20 Gy, for effective treatment (Le, et al., 2017). As the radiation dose increases, the risk of radiation-induced side effects also increases, as recognized by international organizations, such as the United Nations Scientific Committee on the Effects of Atomic Radiation and International Commission on Radiological Protection (ICRP) (Wijma, et al., 2024 ; Wojcik, 2022; Charles, 2008). This is because higher doses not only intensify the primary radiation but also increase scatter radiation, which can affect surrounding healthy tissues (Albano, et al., 2021; Ismail, et al., 2024). On the other hand, according to the World Health Organization, ensuring radiation safety in radiotherapy is essential to protect patients and must include justification of procedures, dose optimization, and adherence to established safety protocols to minimize unnecessary exposure (World Health Organization, 2008).

Several studies conducted both *in vitro* and *in vivo* on humans and rats have shown that gamma rays significantly affect blood cells. Ismail, Hamad and Harki, (2012) observed a notable decrease in red blood cell (RBC), white blood cell (WBC), and platelet (PLT) counts when exposed to a radiation dose rate of 1.1 mSv/h, with statistically significant differences. In another study, by Abojassim, Jaffat and Hassan, (2015) exposure to 6 Gy of X-rays was found to significantly reduce RBC, hemoglobin (HGB), hematocrit (HCT), mean corpuscular volume (MCV), and

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†Corresponding author's e-mail: bazhdar.sh.mohammed@su.edu.krd

mean corpuscular hemoglobin (MCH), with statistically significant differences ($p \leq 0.05$). Similarly, in the study by Taqi, et al. (2018) long-term exposure to X-rays in diagnostic technicians resulted in a significant ($p < 0.05$) decrease in RBC, lymphocytes (LYM), HGB, and HCT compared to the control group. Furthermore, Surniyantoro, et al. (2019) reported that while WBC, HCT, MCV, and LYM levels were significantly lower in radiation-exposed individuals compared to controls, RBC and Monocyte counts were notably higher. In addition, RBC levels showed a significant correlation with the equivalent dose ($p = 0.001$). In addition, Gul, Sengul and Demir, (2024) demonstrated that exposure to 16 Gy and 32 Gy of X-rays, both as a single dose and in fractionated form, led to a significant decrease in WBC, RBC, HGB, and PLT, with a statistically significant probability of occurrence ($p < 0.05$). Furthermore, in a study done by Ismail, et al. (2024) the effect of gamma radiation exposure and duration of exposure produce a great impact on WBC, RBC, LYM, LYM percentage (LYM%), and Granulocyte, with significant changes ($p \leq 0.05$). Berpan and Janhom, (2025) analyzed data from cancer patients undergoing radiotherapy at a dose of 10 Gy, considering treatment location and complete blood count (CBC), WBC count, PLT, and Neutrophils (NEU). Regression analysis during therapy explained approximately 10%, 30%, and 40% of the variance in WBC count, NEU, and PLT count, respectively. However, no studies have specifically examined the effects of high-dose gamma radiation on blood parameters during GKRS, nor have they compared the impact of exposure duration between different dose levels. While GKRS is highly targeted, and the primary focus of its calibration is to ensure precise dose delivery to intracranial lesions, standard calibration protocols do not address scatter or leakage radiation to other body organs.

This study evaluated extracranial absorbed dose, effective dose, and side effects in patients with trigeminal neuralgia who receives 80 Gy and meningiomas who receives 20 Gy in average, allowing for a comparison between these treatment doses. Scatter radiation exposure to various body regions was measured too by using a Radiacode 103 dosimeter. Blood samples were collected before, after, and about 20 days post-treatment to assess effects on blood parameters. The findings provide insights into short- and long-term health risks, highlighting differences in the impact of the two radiation doses.

II. Materials and Methods

A. Study Area and Participants

A prospective analysis was studied on patients diagnosed with meningiomas and trigeminal neuralgia, who underwent frame-based ^{60}Co stereotactic radiosurgery at Erbil Teaching Hospital in the Kurdistan region of Iraq. The treatments were administered using the Leksell Gamma Knife ELEKTA Perfexion™ system (Fig. 1). Patients who received the lowest recommended dosage (meningiomas) and those who received the highest suggested dosage (trigeminal neuralgia) have been taken according to protocols (Gong, et al., 2022, Barzaghi, et al., 2021). A total of 20 patients have been taken, equally divided into two groups, receiving dosages of 20 Gy (median age 41 years; range 25–71 years) and 80 Gy (median age 43 years; range 36–77 years) from June 15, 2024 to December 6, 2024 (Table I). Blood samples of 3 mL were collected from each patient before treatment, after treatment, and again 20 days following treatment. All procedures involving these consecutive patients were conducted in accordance with the guidelines of the Salahaddin University Human Ethics Committee (approval number 4S/269, dated June 30, 2024), based in Erbil, Kurdistan region, Iraq.

B. Nuclear Radiation Dosimeter and Spectrometer

For measuring leaking radiation three same models of the RadiaCode (RC) 103 nuclear radiation detector and spectrometer – RC-103-004240, RC-103-004284, and RC-103-004378 – were utilized to measure leakage radiation exposure from the GKRS. These devices have an energy measurement range for gamma radiation from 0.02 MeV to 3 MeV and a dose rate range of 0.02–20 mSv/h. The dosimeters were calibrated in a certified reference laboratory in line with the ISO 4037–1:2020 standard (Qian, et al., 2021). Calibrations were conducted in July 2024 using Cesium-137 (^{137}Cs) as the reference source with 8.2 ± 0.4% full-width height maximum (Hussein, Salih and Sedeeq, 2021). The background radiation dose rate (μSv/h) inside the GKRS room (560 × 700 cm^2) was first measured at a height of 110 cm from the floor. The dose rate was averaged and recorded for each square

Fig. 1. The Gamma knife ELEKTA perfexion™ 2006.

TABLE I
Features of the Population in the Study. Gy=Gray

Characteristics	Highest dosage lesions	Lowest dosage lesions
Number of patients	10 cases (3 males and 7 females)	10 cases (4 males and 6 females)
Median age (year range)	43 (36–77)	41 (25–71)
BMI (kg/cm^2) Median (range)	23.5 (23.8–29.8)	25.5 (18.1–30.2)
Place of residency	Erbil (40%), Mosul (30%), Salahaddin (20%), Duhok (10%)	Erbil (40%), Sulaymaniyah (%20), Mosul (20%), Salahaddin (10%), Kerkuk (10%)
Prescription dose at 100% Gy	80 Gy at 100%	20-28 Gy at 100%
Median (range)	80 (only 80 Gy used)	20 (20–28)
Standard (limit)	Standard (80–85 Gy) (Boling, et al., 2019)	Standard (20–28) (Lee, et al., 2017)
Median time exposure in minutes (range)	58.2 (41–66.8)	19.4 (7.7–39)

BMI: Body mass index

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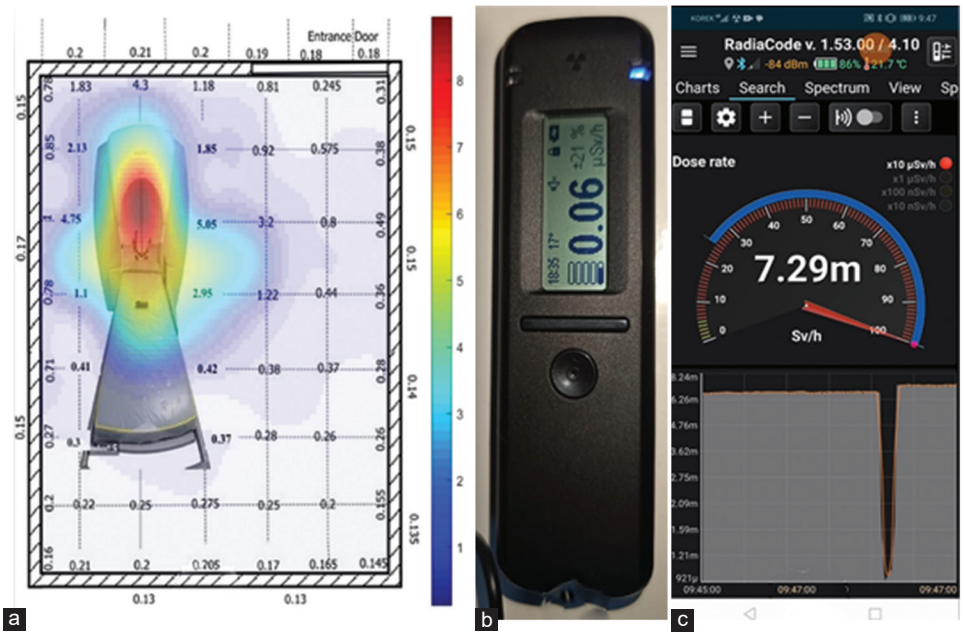

Fig. 2. The map of treatment room and related measurements: (a) Room layout showing background radiation levels recorded at one-meter intervals, (b) RadiaCode 103 nuclear radiation detector and spectrometer, and (c) Huawei mobile screen used for monitoring dose and absorbed dose rate.

meter, as shown in (Fig. 2). In (Fig. 2a), the heatmap uses a color gradient, with blue indicating lower radiation levels and red representing higher radiation levels measured by RCs dosimeters (Fig. 2b). As can be seen, there is a notable concentration of radiation near the central treatment gate. Approximately 1 m away from the gate, the dose distribution decreases exponentially, showing a low value that falls within the safety range as per ICRP guidelines (Boice, et al., 2020). In addition, the dosimeters were controlled and read through a mobile system through a Bluetooth connection, allowing for real-time tracking of the dose and dose rate outside the treatment room during the treatments (Fig. 2c).

According to previous research, phantom measurements demonstrate that there is no significant difference in the absorbed dose at various depths (Hasanzadeh, et al., 2006). Therefore, we can estimate the depth (organ) dose by placing dosimeters at the surface of the patient's skin, as the surface dose is comparable to the depth dose. Then, the average scatter dose rate was measured using an 8 mm collimator. Each patient had radiation doses measured at seven specific anatomical positions to capture dose variation across the body. The targeted measurement sites included the Face (A), Neck (B), Chest (C), Abdomen (D), Gonad (E), Knee (F), and Feet (G) (Fig. 3).

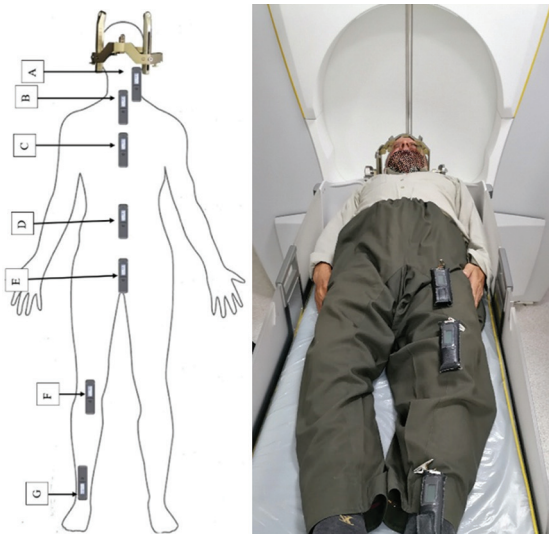

Fig. 3. Patient positioning and dosimeters placements. Left: Schematic representation highlighting dosimeter placement sites: A (head), B (neck), C (chest), D (abdomen), E (gonads), F (knee), and G (feet). Right: A patient secured in the gamma knife radiosurgery frame with dosimeters applied to different body regions.

C. CBC Tests and Blood Analysis

A 3 mL of blood were collected from all individuals a few minutes before treatment to serve as control samples. The samples were collected in vacutainer tubes containing the anticoagulant ethylenediamine tetraacetic acid and gently inverted to prevent clot formation (Elmali, et al., 2024). The same amount of blood was extracted after about 2 h from the treatment. The obtained blood samples were stored in the refrigerator at 4–8°C until measured (Van Balveren, et al., 2017; Amini, et al., 2021). The blood sample was tested using the MEDONIC M32M cell counter and analyzer, which provides 22 hematological blood parameters, such as WBC, RBC, HGB, HCT, and PLT. Other indices, such as MCH, Mean platelet volume, Red cell distribution width (RDW), Plateletcrit, Mean corpuscular hemoglobin concentration, and Platelet distribution width were also reported (Ismail and Abdulla, 2021; Mustafa, Yaba and Ismail, 2020).

D. Statistical Analysis Method

Variation of blood parameters were calculated based on comparison with control sample as well as the results

are presented as the average (Ave.) ± standard deviation, and statistical significance is evaluated using a repeated measurement one-way analysis of variance followed by Dunnett multiple comparison test for *post hoc* comparisons to compare the ratio of changes in blood components between the 20 Gy group and the 80 Gy group with control (Uthirapathy and Tahir, 2021). A p-value below 0.05 is regarded as statistically significant. All statistical analyses were performed using GraphPad Prism software version 8.

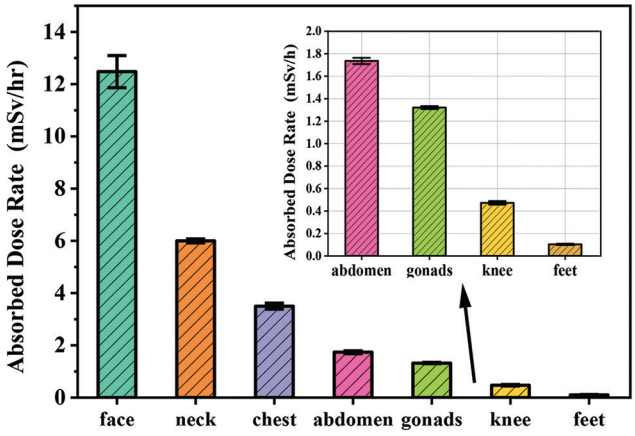

Fig. 4. Absorbed dose rate for different body parts received from scatter radiation of an 8 mm collimator.

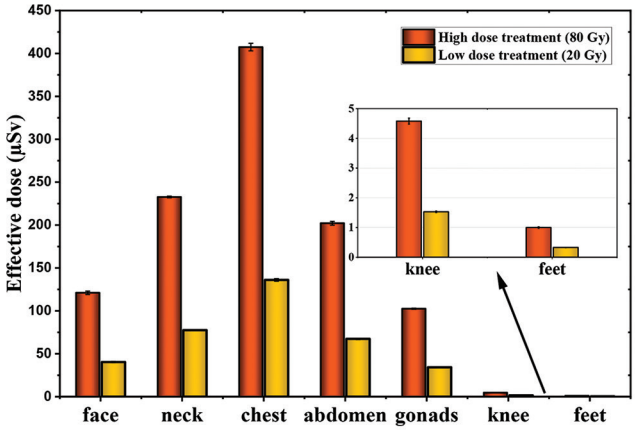

Fig. 5. Comparison of effective dose distribution across different body parts for 80 Gy and 20 Gy treatment cases of trigeminal neuralgia and meningiomas brain lesions.

III. Results and Discussion

Table II shows the radiation dose rates at various distances when using an 8 mm treatment beam collimator for different patient body parts undergoing GKRS for high-dose treatment cases, such as trigeminal neuralgia and low-dose treatment cases, such as meningiomas. It illustrates the radiation received by each body part during treatment. The highest dose rates are observed at the face and neck, significantly higher than those received by other body parts. In contrast, the abdomen, pelvis, knee, and feet receive progressively lower doses. Effective dose values were also calculated following the ICRP 103 guidelines (Nenot, et al., 2009; Charles, 2008).

(Fig. 4) illustrates the scattering of the gamma beam across the patient's body, following an exponential decrease with increasing distance from the source to extracranial body sections. The absorbed dose rates, presented from the face to the furthest body parts, highlight the minimal and maximal values measured in mSv. The inset plot emphasizes the lower dose regions, showing a clear reduction in absorbed dose with increasing distance from the prescribed dose because radiation intensity decreases exponentially with distance due to attenuation and the inverse square law, resulting in higher absorbed dose rates closer to the source.(Fig. 5) presents a comparison of the effective dose (μSv) measured at different body regions following GKRS under two treatment conditions: High-dose (80 Gy) and low-dose (20 Gy). Across all body sites, the effective dose is higher in high-dose treatments because greater photon flux produces more scatter radiation, and each organ has its own sensitivity to radiation, influencing how much dose contributes to overall risk. The effective dose for high-dose treatments is typically 3 times greater than that for low-dose treatments across all body regions. The chest exhibits the highest effective dose among all regions, exceeding 407 μSv in the high-dose group while receiving 136 μSv in the low-dose group. Similarly, the neck receives a substantially higher dose under the high-dose treatment, exceeding 230 μSv, while the low-dose group remains below 100 μSv. The abdomen and gonads also follow this trend, with effective doses in the high-dose group being significantly greater than those in the low-dose group. In contrast, the knee and feet receive considerably lower doses compared to other body regions, with values remaining below 5 μSv. Despite their low exposure, the high-dose

TABLE II
Measurements of the Mean Leakage Gamma Radiation dose from 8 mm Collimator for Extracranial Body Organs in Patients Undergoing Gkrs

Body parts	Average dose rate (Average±SD) in (μSv/h)	Average absorbed dose (high-dose, 58.2 min [μSv])	Average absorbed dose (low-dose, 19.4 min [μSv])	Tissue weighting factors	Effective dose in high-dose treatment (μSv)	Effective dose in low-dose treatment (μSv)
Face	12476±205	12102±199	4034±66	0.01	121±2	40±0.7
Neck	5996±26	5816±25	1939±8	0.04	233±1	77±0.3
Chest	3499±37	3395±37	1132±12	0.12	407±4	136±1.5
Abdomen	1736±18	1684±18	561±6	0.12	202±2	67±0.7
Gonads	1320±9	1280±8	427±3	0.08	102±0.7	34±0.2
Knee	472±10	458±10	153±3	0.01	5±0.1	1.5±0.03
Feet	103±3	100±3	33±1	0.01	1±0.03	0.3±0.01

SD: Standard deviation

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treatment still leads to a relatively greater dose than the low-dose treatment at these sites.(Table III and Fig. 6) represents bar graphs to compare the effects of radiation exposure on hematological parameters based on short-term change (STC) and long-term change (LTC) for both doses. As can be seen, WBC, RBC, PLT, LYM, LYM%, HGB, HCT, RDW%, platelet large cell count (p-LCC), and platelet large cell ratio (p-LCR). Low-dose exposure induces minimal changes, with most parameters remaining comparable to the control. In contrast, high-dose exposure (80 Gy) leads to significant alterations. RBC, WBC, and HCT decrease notably, particularly in LTC80 Gy, indicating a stronger impact with prolonged exposure. PLT-related parameters show mixed responses: PLT, p-LCC, and p-LCR increase significantly in LTC80 Gy, suggesting a compensatory response, while RDW% also rises in LTC80 Gy, indicating increased variability in RBC size. LYM counts rise significantly in STC80 Gy and LTC80 Gy, with a stronger effect in long-term exposure, and LYM% also increases in LTC80 Gy. HGB levels remain stable across most groups but show a slight

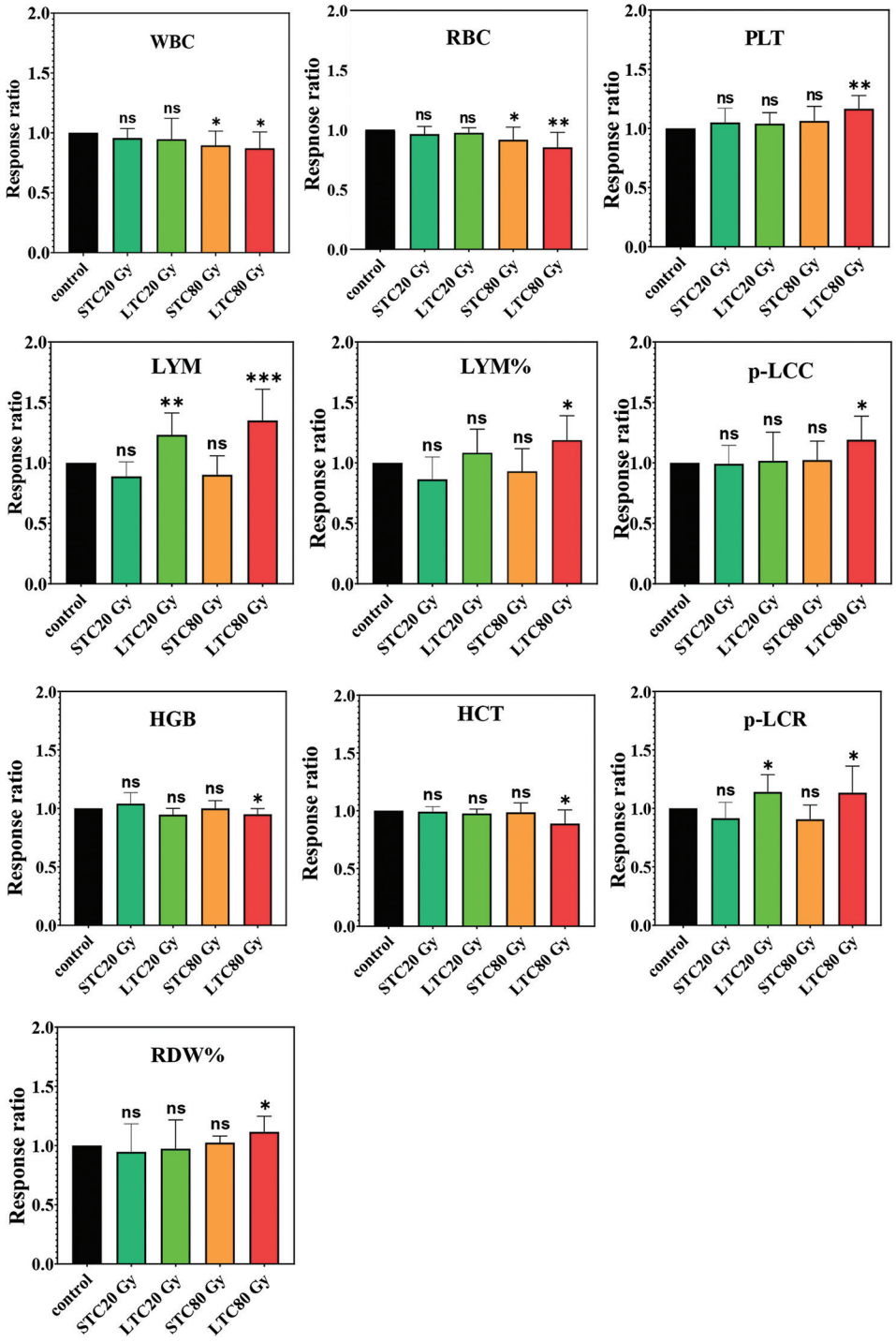

Fig. 6. Short term change and Long-term Change of blood parameters at different radiation doses versus control ($p \leq 0.05$).

TABLE III
BLOOD PARAMETER CHANGES IN RESPONSE TO STC AND LTC RADIATION EXPOSURE

parameters	STC20 (Average±SD)	p-value[1]	LTC20 (Average±SD)	p-value	STC80 (Average±SD)	p-value	LTC80 (Average±SD)	p-value
WBC	0.95±0.08	ns	0.95±0.18	ns	0.9±0.12	*	0.87±0.14	*
LYM	0.89±0.12	ns	1.23±0.18	**	0.9±0.16	ns	1.35±0.26	***
LYM%	0.87±0.16	ns	1.12±0.21	ns	0.93±0.15	ns	1.12±0.2	*
MID	0.86±0.14	ns	1.11±0.22	ns	0.95±0.14	ns	1.04±0.7	ns
MID%	0.87±0.13	ns	1.06±0.27	ns	1.01±0.23	ns	1.08±0.32	ns
GRA	1.02±0.14	ns	0.95±0.19	ns	1.00±0.20	ns	0.89±0.17	ns
GRA%	1.05±0.07	ns	0.97±0.10	ns	1.12±0.26	ns	1.08±0.46	ns
RBC	0.98±0.04	ns	0.97±0.05	ns	0.94±0.08	*	0.89±0.10	**
HGB	1.05±0.11	ns	0.94±0.06	ns	0.99±0.08	ns	0.95±0.05	*
HCT	0.98±0.04	ns	0.97±0.03	ns	0.98±0.07	ns	0.91±0.09	*
MCV	0.99±0.02	ns	1.01±0.03	ns	0.98±0.03	ns	0.97±0.05	ns
MCH	0.99±0.05	ns	0.97±0.05	ns	0.99±0.03	ns	1.00±0.06	ns
MCHC	1.02±0.04	ns	0.97±0.05	ns	1.01±0.03	ns	1.06±0.15	ns
RDWa	0.94±0.13	ns	1.05±0.11	ns	1.01±0.07	ns	1.06±0.12	*
RDW%	1.04±0.35	ns	1.03±0.09	ns	1.02±0.06	ns	1.04±0.14	ns
PLT	1.03±0.12	ns	1.04±0.08	ns	1.05±0.09	*	1.12±0.11	*
MPV	0.97±0.06	ns	1.04±0.09	ns	0.99±0.06	ns	1.03±0.10	ns
PDWa	0.97±0.12	ns	0.96±0.09	ns	1.00±0.10	ns	1.00±0.11	ns
PDW%	1.02±0.07	ns	1.00±0.05	ns	1.04±0.11	ns	1.04±0.10	ns
PCT	1.02±0.16	ns	1.01±0.13	ns	1.06±0.09	ns	1.08±0.13	ns
p-LCR	0.98±0.07	ns	1.02±0.19	*	0.93±0.09	ns	1.12±0.15	*
p-LCC	1.01±0.13	ns	1.04±0.14	*	1.05±0.14	ns	1.14±0.18	*

[1]ns: Non-significant, * = Significant (p≤0.05), ** = More significant (p≤0.01), *** = Highly significant (p≤0.001). LTC: Long-term change, STC: Short-term change, SD: Standard deviation, WBC: White blood cell, LYM: Lymphocytes, RBC: Red blood cell, HGB: Hemoglobin, HCT: Hematocrit, MCV: Mean corpuscular volume, MCH: Mean corpuscular hemoglobin, MCHC: Mean corpuscular hemoglobin concentration, RDW: Red cell distribution width, PLT: Platelet, MPV: Mean platelet volume, PDW: Platelet distribution width, PCT: Plateletcrit, p-LCR: Platelet large cell ratio, p-LCC: Platelet large cell count

decline in LTC80 Gy. Overall, hematological parameters are more sensitive to high radiation because radiation severely affects the bone marrow, where blood cells are produced.

As can be seen, in the cases of 20 Gy rescripted dose resulted in a smaller percentage change in blood parameters compared to 80 Gy, which required a higher dose of radiation for treatment. The results are in agreement with most previous works done by (Ismail, Hamad and Harki, 2012; Abojassim, Jaffat and Hassan, 2015; Taqi, et al., 2018; Surniyantoro, et al., 2019; Gul, Sengul and Demir, 2024; Ismail, et al., 2025; Berpan and Janhom, 2025) which show that increase does and exposure time produces high impact on blood components. The effective doses in high-dose and low-dose treatments across all assessed body regions ranged from 1.5 μSv to 407 μSv, all of which remain substantially lower than the ICRP's recommended dose limit for the general public. On average, the effective doses in high-dose treatments were approximately 3 times higher than those in low-dose treatments, reflecting the extended treatment duration and radiation exposure in the high-dose group (Charles, 2008; World Health Organization, 2008). It is important to note that while patients also received additional diagnostic radiation through computed tomography scans and X-rays for stereotactic planning, these doses were not included in the present analysis, which focuses solely on the radiation exposure resulting from GKRS.

IV. Conclusion

The study assessed the safety of dose-staged GKRS on organs by calculating effective doses across different body regions and analyzing the short- and long-term radiation effects on blood components. We observed that the scattering of the gamma beam from the 8 mm collimator within the patient's body follows an exponential pattern based on the distance from the source to extracranial regions. Across all body regions, leakage radiation is higher in high-dose treatments (80 Gy) compared to low-dose treatments (20 Gy) due to the increased radiation output and intensity used for higher doses. Most hematological parameters showed significant changes that were dependent on high-dose and long-term exposure. This finding is important for GKRS staff to consider when treating patients receiving high radiation doses, emphasizing the need for precise treatment planning and shielding to ensure the radiation remains both effective and safe.

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