ORIGINAL ARTICLE

Out-of-Field Doses in Breast and Pelvic Photon Radiotherapy

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ABSTRACT

A retrospective dosimetric analysis was conducted using treatment planning systems from two radiotherapy centers in Cross River State, Nigeria, equipped with advanced linear accelerators delivering Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT), to investigate the levels of out-of-field radiation doses in modern photon radiotherapy and strategies to minimize exposure to normal tissues. A total of 88 patient treatment plans (41 for pelvic cancer and 47 for breast cancer) were purposively selected from archived records. These plans included a range of clinically approved techniques and varied planning target volumes (PTVs), reflecting typical clinical scenarios. Out-of-field radiation doses were evaluated at fixed distances of 2.5 cm, 5 cm, and 10 cm from the edge of the treatment field. Dose-volume histogram (DVH) data were extracted from the treatment planning system and supplemented by phantom or in vivo measurements when available.The study compared the peripheral dose distributions between treatment modalities and anatomical regions. Results showed that out-of-field doses consistently declined with increasing distance from the treatment field but remained measurable and clinically relevant even at 10 cm, indicating the persistent impact of scatter and leakage radiation. Pelvic treatments exhibited significant modality-based dose differences, particularly at 5 cm, while breast cancer treatments revealed statistically significant differences at all measured distances. VMAT treatments were generally associated with higher and more variable out-of-field doses than IMRT. Larger PTV sizes were directly correlated with increased peripheral radiation exposure. To mitigate out-of-field doses, the study recommends optimizing beam arrangements, minimizing PTV sizes when feasible, and employing shielding. Continuous dose monitoring and quality assurance practices are essential, alongside exploring emerging technologies. This study highlights the importance of treatment planning decisions in reducing unnecessary radiation exposures to the surrounding normal tissues and supports the need for individualized, safety-conscious radiotherapy strategies.

Keywords: Radiotherapy, radiation safety, intensity-modulated radiation therapy, volumetric modulated Arc therapy

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INTRODUCTION

Recently, early diagnosis of cancers and improvements in treatment techniques and therapeutic strategies have led to an increasing success of cancer treatments[1]. Radiotherapy is a widely used treatment modality for cancer patients, where ionizing radiation is used to kill cancer cells. However, while radiotherapy is focused on delivering high doses to the tumor, there is an unavoidable radiation exposure to surrounding healthy tissues. Among the different techniques involved, radiation therapy is used nowadays in more than 50% of cancer treatments[2]. In radiation therapy, peripheral dose or out-of-field doses is important when anatomical structures with very low dose tolerance are involved. Tissues

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such as spinal cord, heart, lungs, kidneys and certain parts of the brain are highly sensitive to radiation, and, even small amounts of radiation exposure outside the intended treatment area can lead to adverse effects like tissue damage, secondary cancers or functional impairment[3]. Advances in radiation therapy technologies, such as intensity-modulated radiation therapy (IMRT) aims to reduce unintended out-of-field doses by enhancing the precision at which the radiation is delivered to the tumor. IMRT uses multiple beams of varying intensities to conform to the shape of the tumor, allowing for highly targeted treatment and sparing surrounding tissues from unnecessary radiation exposure[4].

Radiation scatter is a notable concern in clinical dosimetry and radiotherapy due to the risks it poses to the patient, mainly, the potential to induce second cancers[5]. Scatter radiation occurs when primary radiation interacts with the body and deviates from its intended path, thus affecting tissues outside the treatment area. Studies have shown that even low doses of scatter radiation can accumulate over multiple sessions, leading to an increase in the risk of secondary cancers such as leukemia. For instance, there is an increased incidence of secondary breast cancer in women treated for Hodgkin's lymphoma as a result of scatter radiation[6].

The primary concern with scatter radiation is its potential to cause genetic and cellular damage in healthy tissues. This risk is especially critical in pediatric patients who have more radiosensitive tissues, thus increasing their chances of developing radiation induced cancer overtime[3]. In both slabs phantoms and human bodies, the scattered dose is due to radiation produced by the accelerator head, or to the interaction between the primary and secondary radiation and the medium. The accelerator head, where the high-energy beams are generated, is a potential source of scatter due to the imperfections in the beam or the design of the machine. Radiation leakage or scatter from the head of the accelerator can contribute to out-of-field doses even when the beam is not directly at those specific tissues[7]. Multileaf collimators (MLC) and electron multileaf collimator (eMLC) have been used to minimize photon and electron scatter respectively from the LINAC head, and in collimating the beam to tumour size[8-11]. The determination of patient whole-body exposures requires experimental measurements since treatment planning software is known to be less accurate at greater distances from the treatment volume[12].

Radiotherapy has undergone considerable development that has established a positive impact on long-term outcomes for cancer patients. This has increased the interest in assessing the risk of radiogenic second cancers, whose induction is associated with the inevitable exposure of tissues outside the treatment field. In order to optimize the outcome, treatment regimens are improved to not only maximize the probability of local tumor control but also to minimize the probability of radio-induced effects to normal tissues. For that, the concept of uncomplicated and cancer-free control probability (UCFCP) has been proposed[13]. This approach requires further knowledge about the carcinogenic potential and deterministic effects of the out-of-field radiation doses which in turn has to be accurately assessed. Although the out-of-field doses are mostly less than 4 Gy, questions remain about the potential association between this level of exposure and adverse effects such as second malignant neoplasms, immunologic dysfunction, cardiovascular disease and neurologic effects[13].

It has recently been shown that even very low dose exposures from computed tomography scans can be associated with the development of subsequent cancer. This topic is currently experiencing renewed interests, particularly as modulated treatments such as intensity modulated radiation therapy are now routinely used in clinical care and tend to result in higher peripheral doses because of longer beam-on times[14]. While out-of-field doses in radiotherapy are often small compared to the dose delivered to the target, they represent a critical aspect of patient safety. In modern radiotherapy, while the primary focus is on delivering precisely high doses of radiation to tumor sites, the inevitable exposure of healthy tissues by out-of-field radiation remains a significant concern[14]. Furthermore, the assessment and quantification of out-of-field doses remain challenging due to the complex geometry of modern radiation treatments and the variability in patient anatomy. However, the problem lies in the insufficient understanding of the magnitude and biological implications of out-of-field doses, as well as the limitations in current dosimetric techniques to accurately model these doses. Monte Carlo (MC) simulations have emerged as

a gold standard for modeling out-of-field doses due to their ability to account for complex photon interactions. This research seeks to address these gaps by evaluating the levels of out-of-field doses while proposing strategies to mitigate the impact of out-of-field radiation on normal tissues during radiotherapy. Of note is that, the current study focused on investigating the out-of-field radiation in photon radiotherapy without any consideration of electron and proton therapies.

METHODS

This study used a retrospective dosimetric analysis to evaluate the out-of-field radiation doses in modern photon radiotherapy treatments for pelvic and breast cancer patients in Cross River State, Nigeria. Treatment plans and dose measurements were evaluated from two radiotherapy centers equipped with advanced linear accelerators capable of delivering Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT). Data was drawn from exposure information of patients who underwent external beam photon radiotherapy for pelvic or breast malignancies at the selected radiotherapy facilities. A purposive sampling method was employed, selecting consecutive patient treatment plans that met the study criteria from the radiotherapy department database within the specified time frame.

A total of 41 pelvic and 47 breast cancer patient treatment plans were used for the study due to availability. These plans represented a range of clinically approved treatment techniques, including IMRT with multiple beams and VMAT with rotational arcs. The planning target volume (PTV) sizes varied across patients, reflecting typical clinical heterogeneity.

Out-of-field doses were quantified at three fixed distances: 2.5 cm, 5.0 cm, and 10.0 cm from the edge of the treatment field. These distances were selected to represent near-field and more distant normal tissue locations potentially at risk of scatter radiation. Dosimetric data were extracted from treatment planning system (TPS) dose-volume histograms (DVHs) and confirmed with in-vivo or phantom measurements when available.

Treatment types were categorized based on beam delivery technique (IMRT or VMAT) and anatomical region treated (pelvis or breast). Dosimetric parameters, including mean dose and standard deviation at each distance, were recorded and statistically analyzed to compare out-of-field dose distributions between treatment modalities.

Descriptive statistics summarized dose distributions, while inferential statistics – Analysis of Variance (ANOVA) assessed the significance of differences in out-of-field doses across treatment groups at each measurement distance. Pearson correlation coefficients evaluated the relationships between out-of-field doses at different distances and their association with PTV volume. A significance level of $p < 0.05$ was used for all tests.

RESULTS AND DISCUSSION

This study evaluated the levels of out-of-field doses delivered in modern photon radiotherapy, comparing different treatment types across two critical anatomical regions: the pelvis and breast. The consistent pattern observed in both regions is a steady decrease in radiation dose with increasing distance from the treatment field edge. This aligns with established radiobiological and physical principles of scatter and leakage radiation, where dose intensity diminishes as distance increases due to attenuation and inverse square law effects. In the pelvic region, doses measured closest to the field edge were notably higher than those further away, with the most considerable variability observed at the 2.5 cm distance. This variability likely reflects complex interplay between individual treatment planning parameters such as beam angles, number of fields, and patient anatomy. Larger planning target volumes (PTVs) were strongly correlated with increased out-of-field doses, highlighting the importance of tumor size and treatment volume in determining scattered dose. This relationship reinforces previous findings in the literature indicating that bigger irradiated volumes increase secondary dose exposure to adjacent tissues[15].

Table 1: Out-of-field dose at varying distances from the target in pelvic cases

DFF (cm)	MD±SD (mGy)	Range
2.50	23.54±5.04	17.95–35.80
5.00	14.48±3.95	9.60–25.50
10.00	6.90±3.17	2.93–15.45

Table 2: Out-of-field dose at varying distances from the target in breast cases

DFF (cm)	MD±SD (mGy)	Range
2.50	26.09±4.80	16.23–33.82
5.00	14.19±2.95	4.14–18.36
10.00	8.14±2.59	1.63–12.56

Table 3: Comparison of out-of-field doses by treatment types in the pelvic region

Treatment Type	N	$(Mean±SD)_{2.5}$	$(Mean±SD)_{5.0}$	$(Mean±SD)_{10.0}$
VMAT (Cervix)	6	23.96±3.66	13.66±1.79	6.57±1.08
VMAT (Prostate)	3	23.64±4.27	13.58±0.21	6.61±1.01
VMAT (Endometrium)	2	22.05±3.38	13.23±1.77	6.96±1.45
VMAT (Bladder)	1	22.97	13.52	6.11
VMAT (Vulva)	1	23.72	25.50	8.57

Table 4: One-way ANOVA of out-of-field dose differences by treatment types in pelvic cancer patients

DFF (cm)	SS_{bg}	SS_{wg}	df_b	df_w	MS_b	MS_w	F-value	p-value
2.50	116.36	899.89	5	35	23.27	25.71	0.90	0.49
5.00	331.10	293.60	5	35	66.22	8.39	7.89	0.00
10.00	27.40	375.68	5	35	5.48	10.73	0.51	0.77

Table 5: Correlation between out-of-field doses and PTV volume in pelvis

		2.5 cm	5.0 cm	10.0 cm	PTV (cm³)
2.5 cm	Pearson Correlation	1	.663**	.736**	.645**
	Sig. (2-tailed)		.000	.000	.000
	N	41	41	41	41
5 cm	Pearson Correlation	.663**	1	.709**	.770**
	Sig. (2-tailed)	.000		.000	.000
	N	41	41	41	41
10 cm	Pearson Correlation	.736**	.709**	1	.797**
	Sig. (2-tailed)	.000	.000		.000
	N	41	41	41	41
PTV (cm³)	Pearson Correlation	.645**	.770**	.797**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	41	41	41	41

**=significant

A particularly important finding in the pelvis was the significant difference in out-of-field doses at 5.0 cm among various treatment types. This suggests that certain modalities or beam arrangements contribute more to scatter and leakage at intermediate distances from the field, potentially due to differences in beam modulation or the complexity of the radiation delivery. Several previous studies reported similar dose variations with advanced techniques like IMRT and VMAT, emphasizing the need for careful treatment planning to balance target coverage with minimizing peripheral dose[15,16].

Comparing the pelvis to the breast region reveals some nuanced differences. While both regions showed a decline in dose with increasing distance, breast treatments exhibited slightly higher out-of-field doses near the field edge than pelvis treatments. This could be related to the more superficial location of breast targets, which may lead to higher scatter and less attenuation before the dose reaches adjacent organs such as the heart and lungs. The clinical relevance of these doses is underscored by emerging evidence linking low-dose radiation to secondary malignancies and cardiac toxicity, particularly in breast cancer radiotherapy[17].

Table 6: Comparison of out-of-field doses by treatment types in the breast region

Treatment Type	N	MD±SD (Gy) (2.5 cm)	MD±SD (Gy) (5.0 cm)	MD±SD (Gy) (10.0 cm)
IMRT	26	26.69±4.67	14.13±2.43	8.00±2.44
VMAT	14	25.94±5.52	14.44±4.07	8.79±2.58

Regarding treatment technique comparisons in breast radiotherapy, both IMRT and VMAT are widely used modalities, each with unique dose distribution characteristics. The results indicate that VMAT tends to have greater dose variability and slightly higher doses at further distances (5 cm and 10 cm) compared to IMRT. This is consistent with the inherent nature of VMAT, which involves continuous gantry rotation and dynamic beam modulation, potentially increasing scatter and leakage. Similarly, evidence showed that VMAT may result in higher peripheral doses despite improved conformity and reduced high-dose volumes to organs at risk[18].

Table 7: Comparison of out-of-field doses between IMRT and VMAT using independent sample t-test in breast cancer radiotherapy

DFF (cm)	t-Statistic	p-Value	DFF (cm)
2.5	0.44	0.67	2.50
5.0	-0.26	0.80	5.00
10.0	-0.93	0.36	10.00

Table 8: One-way ANOVA of out-of-field dose differences by treatment types in breast cancer patients

DFF (cm)	SS_{bg}	SS_{wg}	df_b	df_w	MS_b	MS_w	F-value	p-value
2.5	1000.12	60.96	16	30	62.51	2.03	30.76	0.00
5.0	397.93	3.19	16	30	24.87	0.10	233.61	0.00
10.0	280.38	28.32	16	30	17.52	0.94	18.56	0.00

Interestingly, the greatest differences between treatment types occurred at 5 cm from the field edge in breast treatments, mirroring findings in the pelvis. This intermediate distance may represent a critical zone where scatter and leakage radiation from beam shaping devices and collimators exert the most influence, depending on the treatment technique. Such findings highlight an opportunity for targeted optimization in treatment planning and machine design to mitigate out-of-field dose while preserving target coverage.

Table 9: Correlation between out-of-field doses and PTV volume in breast

		2.5 cm	5 cm	10 cm	PTV (cm^3)
2.5 cm	Pearson Correlation	1	.689**	.369*	.355*
	Sig. (2-tailed)		.000	.011	.014
	N	47	47	47	47
5 cm	Pearson Correlation	.689**	1	.676**	.236
	Sig. (2-tailed)	.000		.000	.110
	N	47	47	47	47

		2.5 cm	5 cm	10 cm	PTV (cm^3)
10 cm	Pearson Correlation	.369*	.676**	1	.357*
	Sig. (2-tailed)	.011	.000		.014
	N	47	47	47	47
PTV (cm^3)	Pearson Correlation	.355*	.236	.357*	1
	Sig. (2-tailed)	.014	.110	.014	
	N	47	47	47	47

The strong positive correlations between out-of-field doses at various distances further indicate a systemic relationship in scatter dose distribution. Higher doses close to the field edge predict higher doses further away, reinforcing the importance of controlling dose near the field border to reduce overall peripheral exposure. Additionally, the modest but significant correlation between PTV volume and out-of-field dose in breast treatments suggests that while tumor size contributes to scatter dose, other factors such as beam energy, modulation complexity, and patient anatomy also play key roles.

Table 10: Comparison of mean dose across the breast and pelvis

Region	MD (Gy) (2.5 cm)	MD (Gy) (5.0 cm)	MD (Gy) (10.0 cm)	Trend
Breast	26.09	14.19	8.14	Sharp drop-off
Pelvis	23.54	14.48	6.90	More gradual

Taken together, these results emphasize the dual influence of treatment technique and anatomical factors on out-of-field dose distribution in modern photon radiotherapy. They underscore the necessity for clinicians and medical physicists to carefully consider both target size and delivery modality when designing treatment plans, especially for regions with critical normal tissues nearby.

CONCLUSION

This study confirms that out-of-field doses in modern photon radiotherapy decrease progressively with distance from the treatment field but remain clinically significant even at distances as far as 10 cm. Both the treatment modality and planning target volume size significantly influence the magnitude of these peripheral doses. Specifically, pelvic treatments showed significant dose differences between treatment types at intermediate distances, while breast treatments demonstrated consistent, statistically significant differences across all measured distances, with VMAT generally associated with higher and more variable doses than IMRT. The strong positive correlations between doses at different distances underscore the systemic nature of scatter radiation in radiotherapy. These findings emphasize the need for careful consideration of treatment technique and volume to minimize radiation exposure to healthy tissues.

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