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Effects of Radiation Dose of Photon and Electron Beam Energies and Angles in Radiation Therapy

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Abstract

This study explores the effects of varying radiation beam energy levels and angles on the doses administered to adjacent healthy tissues and tumors during cancer treatment. While electron beams are best suited for superficial tumors because of their shallow penetration depth, photon beams produced by linear accelerators are useful for deep-seated tumors. Radiation doses were measured at different angles with 6 MV and 15 MV photon beams at 0° and 60° and with 6 MeV, 12 MeV, and 15 MeV electron beams at 0° and 15°. The findings demonstrate that larger angles and higher energy produce higher doses at different positions in photon therapy. Energy levels in electron therapy have a greater effect on dose distribution than angles. Our linear regression model analysis found that energy level angles and dose measurements in photon therapy strongly correlate with high R^2 scores (above 0.8). Substantial and inconsistent correlations were observed with electron therapy. Despite these variations, a positive correlation was seen between various dose measurements for both treatments. These results emphasize the significance of choosing the right angles and energy levels to maximize treatment efficacy and minimize harm to healthy tissues. The use of these treatment protocols in clinical settings is supported by comparing our results with international standards which guarantee safety and efficacy.

Keywords: Photon Therapy; Electron Therapy; Effectiveness; Radiation; Dose

Introduction

Cancer is the second leading cause of death globally, responsible for 9.6 million deaths annually, as estimated by the World Health Organization (1). A 70% increase in new cancer cases is anticipated over the next 20 years, disproportionately affecting low- and middle-income countries. In addition to its significant physical and psychological toll, cancer imposes a major burden on healthcare systems and economies (2). Addressing this global challenge requires effective strategies for prevention, early detection, and treatment. Radiation therapy, which utilizes ionizing radiation, is a critical component in the treatment of cancer. Radiation therapy works by damaging the DNA of cancer cells, either killing them or inhibiting their ability to reproduce. The aim is to deliver a sufficiently high radiation dose to the tumor while minimizing the damage to surrounding healthy tissues and

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organs (3). This requires highly precise radiation delivery, achieved using photon and electron beams, each of which has distinct dose distribution characteristics. The accurate delivery of these beams is crucial to ensure effective treatment.

Photon beams, generated by linear accelerators, can penetrate deep into the body, making them suitable for treating tumors located deep within tissues. High-energy photon beams, such as 6MV and 15MV, are particularly effective. While 6MV beams penetrate to moderate depths, 15MV beams provide deeper tissue penetration while sparing the skin from excessive radiation damage. Beam angles play a critical role in optimizing dose distribution, as greater angles can improve dose uniformity and minimize exposure to surrounding healthy tissues (4). In contrast, electron beams are more effective for treating superficial tumors because they have limited penetration. These beams operate within a range of 6-15 MeV, delivering targeted doses to surface-level tumors while sparing deeper tissues. However, electron beams are less effective for treating complex or deep-seated tumors near critical structures, as their depth control is limited. Recent advances in electron beam technology, such as Very High Energy Electrons (VHEEs), offer rapid dose delivery and greater precision, but they carry the risk of exposing tissues behind the tumor (5).

Photon therapy is particularly advantageous for pediatric patients, as it allows for more precise targeting of tumors with minimal impact on surrounding healthy tissue. This helps reduce the risk of long-term side effects and improves local tumor control (6). Proton therapy, though still an emerging technology, offers a limited range of radiation, which reduces exposure to healthy tissues outside the tumor. However, proton therapy requires sophisticated equipment for adjusting energy and beam angles (7, 8). This study aims to enhance the safety and efficacy of radiation therapy at Bhaktapur Cancer Hospital in Nepal by examining how varying beam angles and energy levels influence dose distribution. By optimizing radiation therapy parameters, the research seeks to maximize tumor control while minimizing side effects, contributing to improved patient outcomes and advancing the quality of cancer care in Nepal.

Materials and Method:

Measurement Setup:

Dose measurements were recorded at five distinct positions (P0, P1, P2, P3, and P4) within the radiation field. P2 lies at the center, with P1 and P0 located on the right side, while P3 and P4 are on the left. Positions P0 and P4 are situated outside the primary field, allowing for the evaluation of dose leakage and peripheral distribution. The measurements focused on both deep doses (HP (10) at 10 mm depth) and shallow doses (HP (0.07) at 0.07 mm depth) to assess the efficacy and safety of the treatments.

Energy Levels:

Photon and electron beam therapies were delivered using a Linear Accelerator (Linac). Photon beams at 6MV and 15MV energies were selected to represent common clinical settings for treating tumors at intermediate and deep depths. Electron beams at 6MeV, 12MeV, and 15MeV were chosen for their suitability in treating superficial tumors. Beam angles of 0° and 60° were used for photons, while 0° and 15° were used for electrons, with these angles mimicking real-world treatment scenarios to optimize dose delivery (9). Using both deep and shallow dose measurements allowed for a comprehensive evaluation of dose distribution and its implications for treatment planning and safety.

TLD Harshaw model:

The TLD Harshaw 6600 Plus is a Thermo-luminescent Dosimeter system used for accurate radiation dose measurements. It measures ionizing radiation exposure by detecting light emitted from a crystal when heated, providing critical data for both deep (Hp (10)) and surface (Hp(0.07)) doses in radiological studies(10). The TLD Harshaw is shown in figure 1.

Fig 1: TLD Harshaw 6600 plus model

Results and Discussion:

Data:

Table 1: Datasets collected using Linac for photons and electrons in different energy levels concerning their angles

Card No.	Therapy	Energy	Angle	Position	HP (10) (mSv)	HP (0.07) (mSv)
1000242	Photon	6 MV	0°	P0	3.06	5.59
1000476				P1	51.37	46.70
1001267				P2	50.36	37.41
1000092				P3	52.76	39.62
1000301				P4	3.41	10.98
1000367		15 MV	0°	P0	3.77	5.74
1000422				P1	48.38	31.53
1000469				P2	42.86	32.69
1000501				P3	45.37	32.56
1000498				P4	4.83	12.43

1000276		6 MV	60°	P0	2.61	2.26
1000235				P1	55.82	50.12
1000392				P2	54.78	46.99
1000446				P3	59.25	50.22
1000255				P4	3.505	7.48
1000279		15 MV	60°	P0	3.451	2.77
1000269				P1	60.85	48.8
1000323				P2	49.97	39.95
1000383				P3	54.68	63.85
1001465				P4	4.78	7.92
1000371	Electron	6 MeV	0°	P0	0.77	1.26
1000096				P1	1.69	1.46
1000096				P2	39.48	41.76
1001241				P3	1.85	41.95
1000271				P4	0.78	0.76
1000350		12 MeV		P0	1.06	1.47
1000406				P1	1.89	1.43
1000503				P2	45.41	46.22
1000222				P3	1.72	56.22
1000390				P4	0.95	1.21
1000228		15 MeV	0°	P0	1.29	1.19
1000420				P1	2.037	2.11
1000296				P2	45.37	44.79
1001139				P3	2.68	46.25
1000254				P4	1.47	1.47
1000464		6 MeV	15°	P0	0.66	0.83
1000382				P1	1.45	1.32
1000389				P2	42.91	45.57
1000460				P3	1.24	40.77
1000253				P4	0.79	0.99
1000347		12 MeV	15°	P0	1.03	1.11
1000345				P1	2.63	1.80
1000404				P2	43.81	63.61
1000280				P3	1.64	43.01
1000345				P4	2.63	1.80

1001090		15 MeV	15°	P0	1.31	1.33
1000386				P1	1.84	2.20
1000434				P2	43.36	61.99
1000472				P3	1.80	62.4
1000374				P4	1.00	1.83

Table 2: Mean and standard deviation of HP (10) and HP (0.07) for both therapy

Therapy	Energy	Θ	μ HP 10	Σ HP10	μ HP 0.07	Σ HP 0.07
Photon	6 MV	0°	32.19	26.44	28.06	18.47
Photon	6 MV	60°	35.19	29.38	31.41	24.33
Photon	15 MV	0°	29.04	22.67	22.99	12.91
Photon	15 MV	60°	34.74	28.23	32.65	26.41
Electron	6 MV	0°	8.91	17.09	17.44	22.28
Electron	6 MV	15°	9.41	18.72	17.89	23.13
Electron	12 MV	0°	10.20	19.68	21.31	27.52
Electron	12 MV	15°	10.35	18.71	22.26	29.25
Electron	15 MV	0°	10.57	19.46	19.16	24.06
Electron	15 MV	15°	9.86	18.72	25.95	33.08

For Photon Therapy**:**

Table 3: R^2 score for photon in different positions using metrics

For Photon		
Position	*Metrics*	*R^2 Score*
P0	*HP (10)*	0.994
	HP (0.07)	0.996
P1	*HP (10)*	0.818
	HP (0.07)	0.784
P2	*HP (10)*	0.975
	HP (0.07)	0.987
P3	*HP (10)*	0.980
	HP (0.07)	0.807
P4	*HP (10)*	0.997
	HP (0.07)	0.985

Table 4: Correlation data for different positions with varying energies and angles with metrics

Correlation for P0					Correlation for P1				
	Energy	*Angle*	*HP10*	*HP007*		*Energy*	*Angle*	*HP10*	*HP0.07*
Energy	1	0	0.89	0.10	*Energy*	1	0	0.10	-0.55
Angle	0	1	-0.44	-0.99	*Angle*	0	1	0.89	0.69
HP10	0.89	-0.44	1	0.53	*HP10*	0.10	0.89	1	0.76
HP0.07	0.10	-0.99	0.53	1	*HP0.07*	-0.55	0.69	0.76	1
Correlation for P2					Correlation for P3				
	Energy	*Angle*	*HP10*	*HP007*		*Energy*	*Angle*	*HP10*	*HP0.07*
Energy	1	0	-0.72	-0.56	*Energy*	1	0	-0.59	0.13
Angle	0	1	0.67	0.81	*Angle*	0	1	0.78	0.88
HP10	-0.72	0.67	1	0.94	*HP10*	-0.59	0.78	1	0.67
HP0.07	-0.56	0.81	0.94	1	*HP0.07*	0.13	0.88	0.67	1
Correlation for P4									
	Energy	*Angle*	*HP10*	*HP0.07*					
Energy	1	0	0.38	0.84					
Angle	0	1	0.31	0.49					
HP10	0.38	0.31	1	0.65					
HP0.07	0.84	0.49	0.65	1					

For Electron Therapy:

Table 5: R^2 score for electron in different positions using metrics

For Electron		
Position	*Metrics*	*R^2 Score*
P0	*HP (10)*	0.990
	HP (0.07)	0.689
P1	*HP (10)*	0.487
	HP (0.07)	0.731
P2	*HP (10)*	0.520
	HP (0.07)	0.802
P3	*HP (10)*	0.726
	HP (0.07)	0.441
P4	*HP (10)*	0.246
	HP (0.07)	0.947

Table 6: Correlation data for different positions with varying energies and angles with metrics

Correlation for P0					Correlation for P1				
	Energy	*Angle*	*HP10*	*HP0.07*		*Energy*	*Angle*	*HP10*	*HP0.07*
Energy	1	-0.37	0.98	0.48	*Energy*	1	-0.37	0.52	0.85
Angle	-0.37	1	-0.51	-0.80	*Angle*	-0.37	1	0.22	-0.32
HP10	0.98	-0.51	1	0.56	*HP10*	0.52	0.22	1	0.42
HP0.07	0.48	-0.80	0.56	1	*HP007*	0.85	-0.32	0.42	1
Correlation for P2					Correlation for P3				
	Energy	*Angle*	*HP10*	*HP007*		*Energy*	*Angle*	*HP10*	*HP0.07*
Energy	1	0	0.72	0.51	*Energy*	1	0	0.60	0.66
Angle	0	1	-0.01	0.73	*Angle*	0	1	-0.60	0.03
HP10	0.72	-0.01	1	0.20	*HP10*	0.6	-0.60	1	0.10
HP007	0.51	0.73	0.20	1	*HP0.07*	0.66	0.03	0.10	1
Correlation for P4									
	Energy	*Angle*	*HP10*	*HP0.07*					
Energy	1	0	0.38	0.84					
Angle	0	1	0.31	0.49					
HP10	0.38	0.31	1	0.65					
HP.007	0.84	0.49	0.65	1					

Table 2 shows the dose distribution statistics for photon and electron therapy across different energies and angles. Photon therapy tends to have higher mean values for both HP (10) and HP (0.07), indicating higher dose delivery both at depth and at the surface. The standard deviation for photon therapy is also higher, indicating more variability in dose distribution. In contrast, electron therapy generally shows lower mean dose values with reduced variability. Photon therapy delivers higher mean doses for HP (10) and HP (0.07) with a larger standard deviation (24.72 mSv), reflecting greater variability in dose distribution, which can impact consistency in clinical outcomes. From table 3 and 5, The R^2 scores for photon therapy across different positions indicate high accuracy in predicting HP (10) and HP (0.07) doses. P0 and P4 show the highest R^2 values, indicating better model fits at these positions. Positions P1 and P3 have slightly lower R^2 values, suggesting higher variability in dose prediction. Electron therapy shows lower R^2 scores overall, particularly for deeper doses (HP (10)). The surface doses (HP (0.07)) are more accurately predicted, especially at P4, which has the highest R^2 for HP (0.07).

Table 4 and 6 show the correlation data shows varying degrees of association between energy, angle, and dose metrics. For photon therapy, P0 shows a strong positive correlation between energy and HP (10), while HP (0.07) is negatively correlated with angle. For electron therapy, energy is strongly correlated with HP (10) and HP (0.07) at most positions. Photon therapy demonstrates higher dose variability and overall dose delivery both at depth (HP (10)) and at the surface (HP (0.07)), which may indicate greater effectiveness but also increased potential for side effects. Electron therapy, with lower and more concentrated doses, suggests better control over surface doses, which may be preferable in treatments where minimizing skin toxicity is a priority. Positions P0 and P4 for photon therapy demonstrate the best model fit and highest dose predictability, while intermediate positions (P1 and P3) show more variability. In electron therapy, surface doses at P4 are most predictable, while deeper doses (HP(10)) are less accurate, particularly at P4 and P1.The strong correlation between energy and HP(10) in photon therapy suggests that energy is a significant factor in dose delivery at depth, while the angle plays a more critical role in determining surface dose (HP(0.07)). In electron therapy, energy has a more consistent influence on both deep and surface doses across positions, with angle having less influence, particularly for deeper doses.

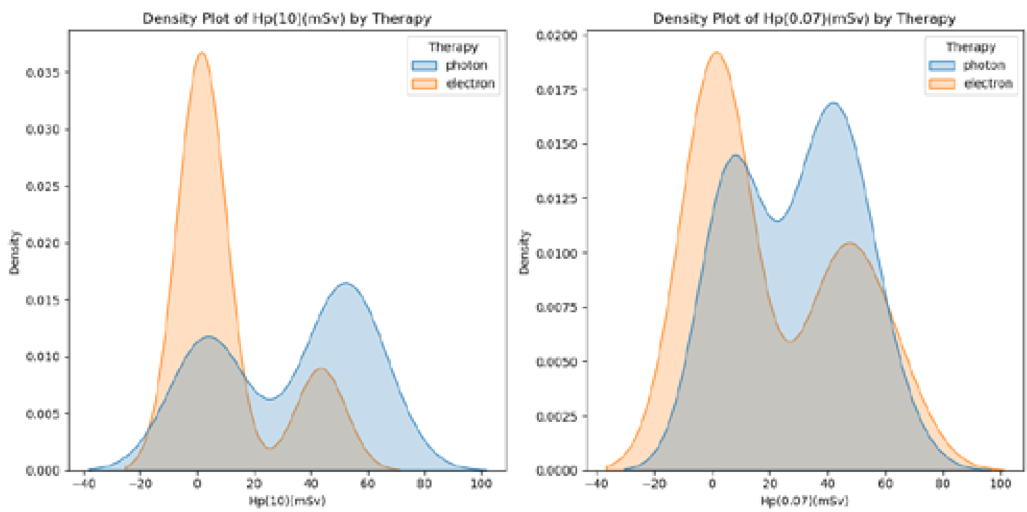

Fig. 2: KDE plots comparing HP (10) (left) and HP (0.07) (right) dose distributions for photon (blue) and electron (orange) therapy

Figure 2 shows Kernel density estimate (KDE) plots, used to compare how photon and electron therapies distribute doses at different tissue depths, focusing on HP (10) for deep doses and HP (0.07) for surface doses. Photon therapy shows broader, higher dose distributions, while electron therapy has lower, more concentrated doses, especially at surface level. For deep tissue doses (HP (10)), photon therapy shows a wider range of dose values with peaks at around 30 mSv and 70 mSv, meaning it often delivers a spread of doses, which can vary. Electron therapy, however, has a sharp peak near 0 mSv, indicating lower and more consistent deep doses. Regarding surface doses (HP (0.07)), photon therapy also shows more variation, with peaks at about 30 mSv and 60 mSv. In contrast, electron therapy again delivers lower surface doses, with a sharp peak around 0 mSv, suggesting minimal surface exposure. In summary, Photon therapy delivers higher and more variable doses, better for treating deeper tissues but with more risk of skin side effects. Electron therapy delivers lower, more consistent doses, making it safer for the skin but less effective for deeper tissue treatment.

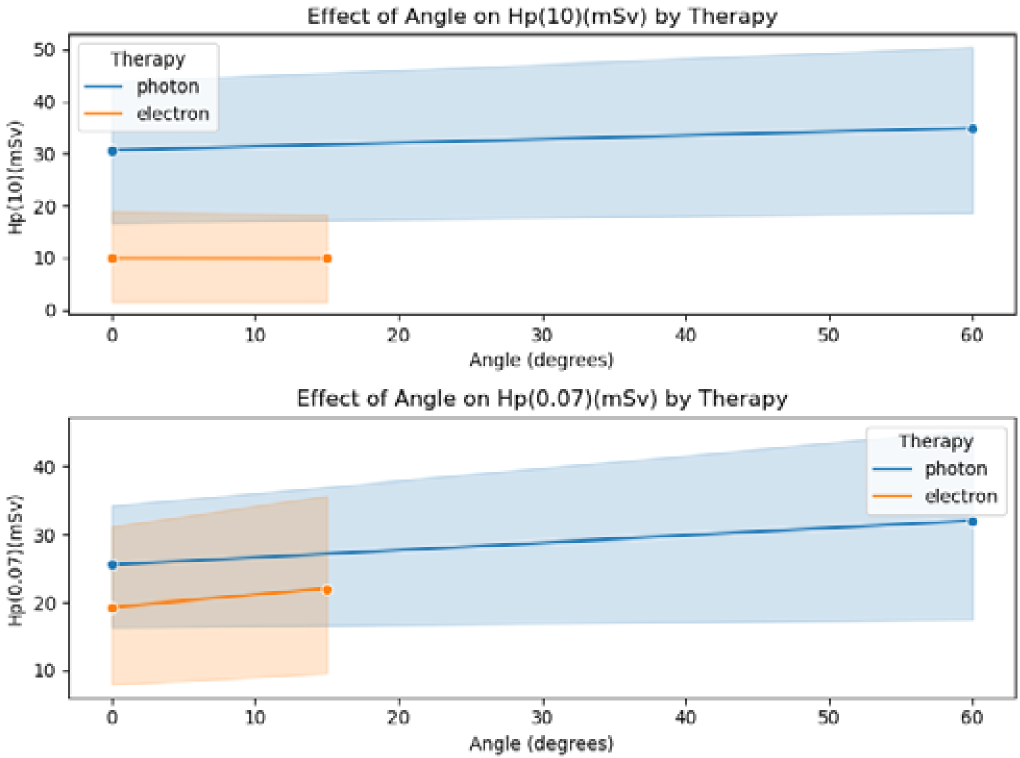

Fig. 3: Effect of radiation angle on HP (10) and HP (0.07) for photon and electron therapies

This study looks at how photon and electron therapies deliver doses to both deep (HP (10)) and shallow (HP (0.07)) tissues as the radiation angle changes. Photon therapy delivers higher doses to both deep tissues (30-35 mSv) and skin (around 30 mSv). The dose slightly increases as the angle grows, suggesting better deep tissue penetration but also higher risks of skin side effects at larger angles. And that of electron therapy delivers lower, more consistent doses to both deep tissues (10-15 mSv) and skin (around 20 mSv), with minimal changes across angles. This makes it safer for the skin but less effective for treating deeper tissues.

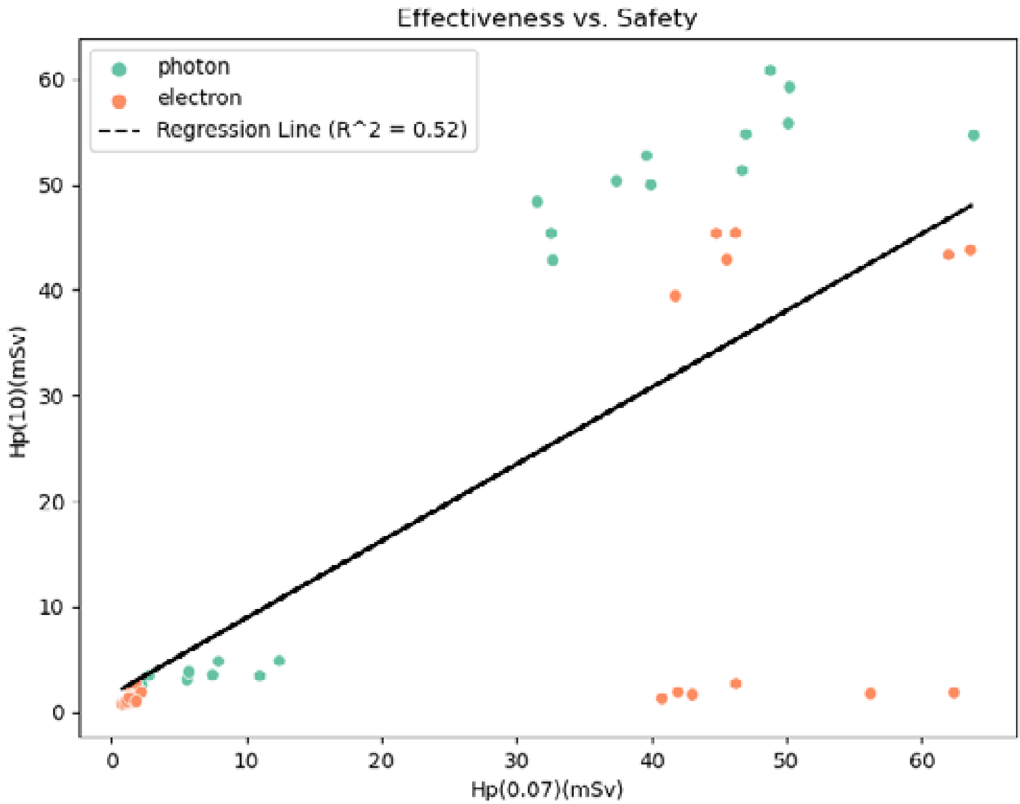

Fig. 4: Relationship between Surface Dose (HP (0.07)) and Deep Dose (HP (10)) for Photon and Electron Therapies.

This study uses a scatter plot to show how surface dose (HP (0.07)) and deep dose (HP (10)) relate to photon and electron therapies. Green dots represent photon therapy, and orange dots represent electron therapy. A black dashed line shows a moderate link between surface and deep dose values. Photon therapy typically gives higher deep doses, which suggests it's more effective but might have higher surface dose risks. The plot shows a strong linear relationship between surface and deep doses. Photon therapy delivers higher doses (up to 60 mSv for both), making it better for deep tumours but riskier for the skin. Electron therapy delivers lower doses (up to 40 mSv), making it safer for the skin but less effective for deep tissues. In short, photon therapy is more effective for deep tumours but increases the chance of skin side effects. Electron therapy is safer for the skin but less effective for deeper targets. The strong R^2 value means deep dose can be predicted by surface dose and position, helping clinicians choose the right therapy based on patient needs. Future studies could focus on improving dose distribution to balance effectiveness and safety.

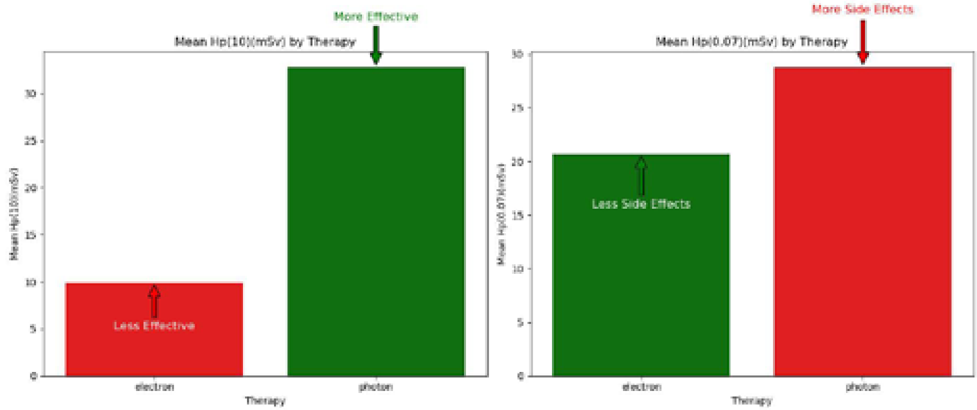

Fig. 5: Comparison of radiation therapy effectiveness and side effects

Figure 5, left chart shows that photon therapy is more effective, delivering a higher HP(10) dose to deep tissues compared to electron therapy. The right chart indicates that photon therapy also has more side effects, with a higher HP(0.07) dose to the skin and shallow tissues. This study looks at how photon and electron radiation therapies work for treating deep tissues and their impact on the skin, using clear data. On the Left side, Photon therapy delivers a higher deep tissue dose of around 30 mSv, making it more effective for treating tumours located deep in the body while Electron therapy, with a lower dose of around 10 mSv, is less effective for deeper tissues because it doesn't penetrate as well. But in the right part, Photon therapy also gives a higher dose to the skin, about 30 mSv, which can lead to more skin problems like redness or burns, and Electron therapy delivers a lower skin dose, around 20 mSv, making it gentler on the skin with fewer side effects. So, Photon therapy is better for treating deep tumours because it delivers more radiation to the target. However, this higher dose also increases the chance of skin issues. Electron therapy is kinder to the skin because of the lower dose, but it isn't as effective for deep tissue treatments.

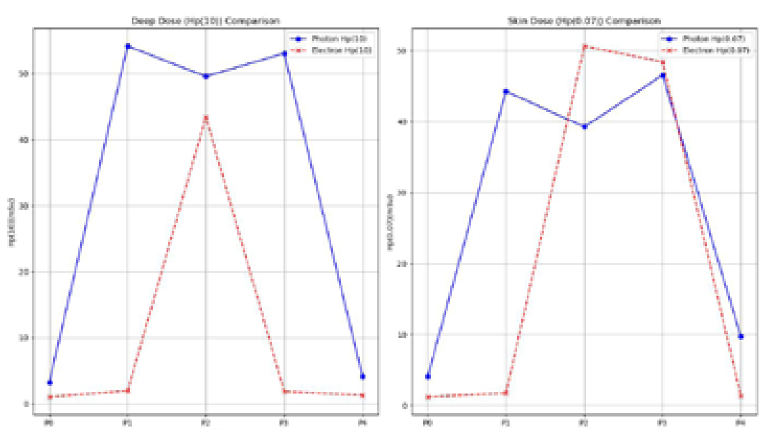

Fig. 6: Comparison of the deep dose (HP (10)) and skin dose (HP (0.07)) for photon and electron therapies across different positions

The left graph shows the deep dose with photon therapy (blue solid line) having higher values than electron therapy (red dashed line) within the field (positions P1, P2, P3). The right graph shows the skin dose, with similar trends observed. Positions P0 and P4 are outside the field. In contrast, electron therapy offers fewer side effects due to its lower HP(0.07) values, making it more suitable for cases where avoiding skin damage is crucial. However, this comes at the cost of reduced effectiveness for deeper tissues, as indicated by the lower HP(10) values. Electron beams, with their superficial energy deposition, are not as effective for treating deep tumors but are beneficial for more localized, shallow treatments where minimizing skin damage is important. The dose distribution for both deep dose (HP (10)) and skin dose (HP (0.07)) was evaluated across five positions (P0 to P4) under a photon field of size 40 x 40 cm at a dose rate of 300 MU/min. Positions P1, P2, and P3 lie within the field, while P0 and P4 are outside the field. Deep dose (HP (10)): The highest dose was observed at P0 (50 mSv) and P4 (52 mSv), despite being outside the field, indicating scatter or leakage contributions. The dose at P2 (the center) was relatively uniform (50 mSv), reflecting effective deep tissue coverage within the field. Skin dose (HP (0.07)): The highest skin dose was recorded at P2 (50 mSv for photons, 48 mSv for electrons), showing uniform skin exposure within the field. Skin doses at P0 and P4 were much lower, reflecting reduced exposure outside the beam area.

The results show that both HP (10) and HP (0.07) values were consistent at P1, P2, and P3, indicating uniform photon beam delivery within the field. P0 and P4, lying outside the beam, experienced lower doses, confirming rapid dose fall-off outside the field. However, higher deep dose readings at P0 and P4 suggest scattering radiation beyond the intended field. The uniformity of HP (10) within the field highlights effective deep dose delivery, which is essential for therapeutic success in targeting tumors. The HP (0.07) measurements show adequate skin dose control, reducing the risk of skin damage. This dose profile ensures both treatment efficacy and patient safety by delivering sufficient deep dose while minimizing skin exposure. The photon beam provided effective dose distribution for deep tissues, with controlled skin doses across the field, supporting the potential for safe and effective therapeutic application.

Conclusion

Photon therapy is highly effective in delivering higher doses to deeper tissues, making it particularly useful for treating deep-seated tumors. However, its effectiveness comes with a higher risk of skin-related side effects due to the increased surface dose. On the other hand, electron therapy is more suited for superficial tumors, providing a safer profile in terms of skin exposure, but it is less effective for treating deeper tissues [11]. The findings from the regression analysis, with a high R^2 value, confirm that both surface dose and position are significant predictors of the deep dose's effectiveness.

For future therapy choices, a balance between treatment effectiveness and safety must be carefully considered. This includes factoring in patient-specific characteristics, tumor depth, and the potential impact on surrounding healthy tissues. Furthermore, future studies should explore ways to optimize dose distribution by refining energy levels, angles, and beam types based on individual patient needs. Tailoring these treatment parameters will be crucial to minimizing side effects while ensuring the tumor receives an adequate dose.

Overall, the study highlights the need for personalized radiation therapy planning, which accounts for both deep and surface dose impacts, to improve clinical outcomes and safety for patients.

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Author's Contribution

The study was designed and conceived by Bijay Raj Neupane, Narendra Khadka, Ram Sharan Karki, and Smriti Baniya. HBB read, modified, edited and approved the final version of the manuscript.

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Conflict of Interest

No, there is no conflict of interest.

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