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Correlation of Dose-Volume Histogram Metrics with Radiobiological Indices in Cervical Cancer Patients Undergoing Brachytherapy

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ABSTRACT

Dose-volume histogram (DVH) metrics are routinely used to evaluate brachytherapy plans for cervical cancer and their association with radiobiological outcomes is seldom verified for individual institutional datasets. This study presents a correlational analysis of DVH metrics with radiobiological indices of 45 cervical cancer patients undergoing brachytherapy at National Hospital, Abuja. CT-based treatment planning was used to contour the high-risk clinical target volume (HR-CTV), intermediate-risk clinical target volume (IR-CTV), bladder, and rectum. DVH metrics (HR-CTV D_{90}, D_{98} and EQD2-converted D_{2cc} for bladder and rectum) were extracted from the treatment planning system (TPS). Tumor Control Probability (TCP) was computed using linear-quadratic (LQ) model, while Normal Tissue Complication Probability (NTCP) was estimated using Lyman-Kutcher-Burman (LKB) model. Pearson correlation analysis was performed using Python to determine the strength and significance of associations between DVH metrics and radiobiological indices. From the results, the mean ± SD doses were found to be 5.78 ± 0.35 Gy (HR-CTV D_{90}) and 4.24 ± 0.29 Gy (IR-CTV D_{90}). TCP modeling yielded high control probabilities for HR-CTV (99.97% for D_{90}; 99.99% for D_{98}) and lower values for IR-CTV (85.38% and 92.04%, respectively). NTCP remained negligible (0.0004%) for both bladder and rectum, with all D_{2cc} values below the 90 Gy EQD2 GEC-ESTRO constraint. Strong positive correlations were observed between TCP and HR-CTV D_{90} EQD2 ($r = +0.889$, $p < 0.001$). In contrast, TCP correlated weakly and non-significantly with HR-CTV D_{98} ($r = +0.239$, $p = 0.1143$). For organs at risk, rectum D_{2cc} showed a strong correlation with NTCP ($r = +0.836$), while bladder D_{2cc} showed a moderate correlation ($r = +0.618$). Therefore, EQD2 form of HR-CTV D_{90} was found to be a significant predictor of tumor control, whereas D_{98} is a poor predictor. These findings support the preferential use of D_{90} and D_{2cc} metrics in brachytherapy plan evaluation and reinforce the validity of GEC-ESTRO constraints in ensuring treatment safety.

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INTRODUCTION

Cervical cancer remains one of the leading malignancies affecting women worldwide, particularly in developing countries where screening programs are limited (Sung *et al*., 2021). Radiotherapy, combining external beam radiotherapy (EBRT) with intracavitary brachytherapy, is the cornerstone of definitive treatment for locally advanced disease, offering superior dose localization to the tumor while sparing surrounding normal tissues (Cibula *et al*., 2018). Brachytherapy, through the placement of applicators in close proximity to the cervix, delivers a highly conformal dose distribution, with the high-risk clinical target volume (HR-CTV) receiving the highest fraction of prescribed dose (Viswanathan *et al*., 2012).

Modern image-guided adaptive brachytherapy (IGABT) relies on three-dimensional imaging modality such as computed tomography (CT) or magnetic resonance imaging (MRI) for target delineation and treatment planning, which has been shown to improve pelvic control and survival (Sturdza *et al*., 2016). Plan quality is assessed using dose-volume histogram (DVH) metrics. For target volumes, D_{90} and D_{98} (the minimum doses covering 90% and 98% of the volume) are standard descriptors of target coverage, while for organs at risk (OARs), the near-maximum doses to small volumes (D_{2cc} and D_{1cc}) are monitored against tolerance constraints recommended by the GEC-ESTRO terms. These constraints are supported by clinical evidence linking D_{2cc} to late toxicity (Georg *et al*., 2011).

However, physical dose metrics alone do not directly express the biological consequences of irradiation. Because EBRT and brachytherapy deliver different fractionation schemes, the concept of the equivalent dose in 2 Gy fractions (EQD2), grounded in the linear-quadratic (LQ) model of cell survival, is essential for summing contributions and comparing plans on a common radiobiological scale (Dale & Jones, 2007). Building on this, radiobiological models such as tumor control probability (TCP) and normal tissue complication probability (NTCP) model provide quantitative estimates of treatment efficacy and toxicity risk (Potter *et al*., 2023).

Despite the routine use of DVH metrics, their degree of association with TCP and NTCP is not always verified for individual institutional datasets. Establishing these correlations is clinically important: a DVH metric that strongly correlates with TCP can serve as a reliable surrogate endpoint for tumor eradication, while metrics weakly correlated with outcome may be misleading in plan evaluation. Similarly, quantifying the correlation between OAR dose metrics and NTCP helps identify which organ is dose-limiting and validates the safety margins applied in planning (Dale & Jones, 2007).

This study therefore investigates the correlation between DVH metrics (HR-CTV and IR-CTV for D_{90} and D_{98}, of bladder and rectum for D_2cc) and radiobiological indices (TCP and NTCP) in 45 cervical cancer patients treated with brachytherapy. This study aims to determine the relationships between dose–volume histogram metrics and model-derived tumor-control and normal-tissue complication probabilities in cervical cancer patients undergoing brachytherapy.

MATERIALS AND METHODS

A Computed Tomography (CT) scanner was used in acquiring images of the 45 patients considered in this research work. Institutional permission from National Hospital, Abuja, was granted following a letter of introduction issued from the department of Physics, Nasarawa State University, Keffi. This study adopted both prospective and retrospective approach for obtaining data from August 2025 to April 2026. For this study, only adult patients (age ≥ 18) diagnosed with cervical cancer (stage IA to IIIB) undergoing cervical cancer were considered, while pregnant patients and patients with significant comorbidities that may affect treatment outcomes (such as severe cardiovascular disease) were excluded. For the brachytherapy dose prescription, total of 21Gy in 3 fractions (7Gy) was adopted for a period of 3 weeks (once per week), while for EBRT, a total of 45Gy in 25 fractions (1.8Gy) was adopted 25 days (7 weeks). Brachytherapy applicator (tandem and ovoid) was installed in all patients for dose delivery to targets. Treatment Planning System (TPS) was used for delineation and contouring of both target (tumor) and organs at risk (bladder and rectum) for treatment session. For the Clinical Target Volume (CTV), High-Risk Clinical Target Volume (HR-CTV) and Intermediate-Risk Clinical Target Volume (IR-CTV) were all contoured with specified dose for each region. For dose delivery, the HR-CTV region includes the entire target volume (the whole cervix) and received the highest percentage of the prescribed dose. This is as a result of the CTV having a close proximity with source (point of delivery). For the IR-CTV region, it received a very low percentage of the prescribed dose as compared to the HR-CTV. This is because of its distance with the source (applicator). The IR-CTV area contains microscopic tumor extension, making it to receive low amount of dose percentage from the prescribed dose. These two regions (HR-CTV and IR-CTV) received doses based on certain volumes (in cm^3) of their delineated regional size. A Jupyter library of Python (Anaconda, V25) programming algorithm was adopted for the computation of both the modeling and Pearson correlation analysis with a statistical significance of $p<0.05$.

Dose-Volume Histogram (DVHs) Metrics

For the dose delivered to both target (tumor) and organs at risk (bladder and rectum), specific metrics were adopted for the dose response analysis. These metrics include HR-CTV D_{90}, HR-CTV D_{98}, and EQD2 for D_2cc. For the target (tumor), D_{90} and D_{98} were used in estimating the dose received by the entire region of the target, while EQD2 D_2cc were used in estimating tissue response at risk (bladder and rectum). These metrics evaluates the volume that absorbs certain amount of doses for both target and organs at risk. This helps in estimating whether the dose received is capable of eradicating the tumor with over-exposure or under-exposure. Similarly, it also help in estimating the amount of dose received by the organs at risk delineated (bladder and rectum). The results for these metrics are presented in Table 1, 2, 3, 4 and 5.

Radiobiological Indices

Tumor Control Probability (TCP) Model

This model uses linear quadratic (LQ) model for estimating factors such as tumor size, dose distribution, and cellular response. In this research work, this model was adopted to estimate the likelihood of eliminating the target tumors after radiation treatment (Dale & Jones, 2007). The Tumor Control Probability (TCP) model used is mathematically given in Equation 1.

$$TCP = e^{-N\times SF} = exp\left[-N \times e^{-(\alpha D-\beta nd^2)}\right] \quad (1)$$

Where: N = number of tumor cells and SF = Survival fraction (LQ model)

For the linear quadratic (LQ) model that forms the framework of tumor control probability (TCP) model, it was adopted in Python programming software for estimating the cell survival rates at different radiation doses. The Linear quadratic (LQ) model used is mathematically given in Equation 2.

$$SF = e^{-(\alpha D-\beta nd^2)} \quad (2)$$

Where: SF = surviving fraction of cells; D = total dose; d = dose per fraction; n = number of fractions; α = linear coefficient and β = quadratic coefficient.

Normal Tissue Complication Probability (NTCP) Model

For the Normal Tissue Complication Probability, Lyman-Kutcher-Burman (LKB) model was adopted to estimate the likelihood of complications in normal tissues resulting from the procedure (Dale & Jones, 2007). The LKB model uses dose-volume with tissue sensitivity and it is mathematically given in Equation 3.

$$LKB = \frac{1}{2}\left[1 + erf\left(\frac{D_{eff}-TD_{50}}{m\times TD_{50}\times\sqrt{2}}\right)\right] \quad (3)$$

Where; erf = error function; m = volume parameter; TD_{50} = tolerance for 50% complication and D_{eff} = effective dose

The effective dose (D_{eff}) that was adopted in estimating the Lyman-Kutcher-Burman (LKB) model in this research is given in Equation 4.

$$D_{eff} = \left(\sum_{i=1}^{N} v_i \times D_i^{1/n}\right)^n \quad (4)$$

Where; D_i = dose bin; V_i = volume fraction and n = volume parameter.

Correlation Analysis

Correlation analysis is a statistical procedure that measures the strength and direction of a linear relationship between two variables. This procedure was employed in this research work in order to establish a relationship between the extracted Dose-Volume Histogram (DVH) metrics and the radiobiological indices modeled. The formula uses Pearson correlation coefficient and is given in Equation 5.

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \quad (5)$$

Where: r = Pearson correlation coefficient; n = number of pairs of scores; x = modeled data for bladder (as x-variable) and y = modeled data for rectum (as y-variable).

RESULTS AND DISCUSSION

Dose Delivered to 90% and 98% of HR-CTV and IR-CTV

Table 1 and 2 shows the dose delivered to the 90% and 98% of both high-risk clinical target volume (HR-CTV) and intermediate-risk clinical target volume (IR-CTV) for all patients. These two regions were delineated for precise delivery of radiation doses thereby taking tumor and affected tissue extension (tumor extent) into consideration. By determining the amount of dose delivered to the higher volume percentage of these two regions (HR-CTV and IR-CTV), proper estimation for better protection of organs at risk was made, leading to smooth modeling and simulation. This

is done to optimize brachytherapy treatment plans for better outcomes.

Table 1: Dose Delivered to 90% and 98% of HR-CTV

Patient	Age (Year)	HR-CTV (cm^3)	HR-CTV	
			D_{90} (Gy)	D_{98} (Gy)
P1	38	65.00	6.30	6.86
P2	46	80.50	5.40	5. 88
P3	55	70.30	5.89	6.37
P4	25	81.50	5.38	5.86
P5	35	64.40	6.31	6.87
P6	46	82.0	5.39	5.87
P7	39	80.20	5.37	5.86
P8	45	75.70	5.67	6.17
P9	49	80.50	5.49	5.99
P10	35	78.70	5.58	6.08
P11	38	67.80	6.21	6.76
P12	46	70.10	5.85	6.37
P13	41	69.30	5.94	6.47
P14	46	76.00	5.76	6.27
P15	49	76.30	5.77	6.28
P16	35	80.40	5.48	5.98
P17	37	69.40	5.95	6.48
P18	47	71.10	6.12	6.66
P19	41	82.20	5.41	5.89
P20	42	71.50	6.13	6.66
P21	33	65.50	6.21	6.76
P22	48	81.10	5.49	5.99
P23	36	78.80	5.58	6.08
P24	35	65.30	6.20	6.75
P25	38	70.10	5.85	6.37
P26	37	69.50	5.96	6.49
P27	44	65.30	6.31	6.87
P28	43	81.50	5.36	5.85
P29	31	70.50	5.86	6.36
P30	46	82.80	5.35	5.86
P31	31	65.50	6.30	6.85
P32	45	80.60	5.37	5.87
P33	47	82.20	5.36	5.86
P34	36	81.90	5.35	5.85
P35	41	71.80	6.14	6.67
P36	37	65.60	6.20	6.75
P37	49	81.40	5.48	5.98
P38	35	82.80	5.36	5.88
P39	48	72.60	6.12	6.65
P40	41	65.50	6.32	6.89
P41	38	80.90	5.37	5.87
P42	39	70.60	5.86	6.38
P43	45	82.50	5.39	5.89
P44	49	65.70	6.31	6.88
P45	32	81.90	5.37	5.87
Average ± SD	40.87 ± 6.20	74.55 ± 6.56	5.78 ± 0.35	6.29 ± 0.38

Table 2: Dose delivered to 90% and 98% of IR-CT

Patient	Age (Year)	IR-CTV (cm^3)	IR-CTV	
			D_{90} (Gy)	D_{98} (Gy)
P1	38	90.00	4.50	4.90
P2	46	99.80	3.60	3.92
P3	55	97.50	4.05	4.41
P4	25	91.10	4.51	4.91

Patient	Age (Year)	IR-CTV (cm^3)	IR-CTV	
			D_{90} (Gy)	D_{98} (Gy)
P5	35	93.90	4.41	4.80
P6	46	98.20	3.96	4.31
P7	39	97.10	4.14	4.51
P8	45	98.00	3.95	4.30
P9	49	99.50	3.69	4.02
P10	35	97.70	4.06	4.42
P11	38	90.50	4.51	4.91
P12	46	94.20	4.42	4.82
P13	41	98.00	3.97	4.31
P14	46	97.40	4.07	4.43
P15	49	90.30	4.50	4.90
P16	35	93.80	4.40	4.81
P17	37	91.00	4.53	4.92
P18	47	99.00	3.87	4.21
P19	41	97.50	4.08	4.44
P20	42	90.90	4.51	4.91
P21	33	94.10	4.42	4.83
P22	48	90.60	4.53	4.92
P23	36	99.70	3.70	4.03
P24	35	97.60	4.06	4.42
P25	38	90.60	4.51	4.90
P26	37	93.90	4.41	4.82
P27	44	96.00	4.23	4.61
P28	43	95.70	4.32	4.70
P29	31	91.30	4.50	4.90
P30	46	93.90	4.40	4.80
P31	31	90.80	4.51	4.91
P32	45	99.50	3.71	4.01
P33	47	97.70	4.05	4.41
P34	36	91.20	4.52	4.93
P35	41	94.40	4.43	4.84
P36	37	91.10	4.54	4.94
P37	49	90.30	3.60	3.92
P38	35	97.50	4.07	4.43
P39	48	90.20	4.53	4.93
P40	41	93.80	4.42	4.81
P41	38	96.00	4.22	4.60
P42	39	95.50	4.30	4.69
P43	45	90.50	4.52	4.91
P44	49	94.00	4.41	4.81
P45	32	96.10	4.21	4.59
Average ± SD	**40.87 ± 6.20**	**94.61 ± 3.22**	**4.24 ± 0.29**	**4.62 ± 0.31**

Brachytherapy D_2cc Evaluation for Bladder and Rectum

Table 3 shows the highest dose received to a $2cm^3$ (D_2cc) volume of bladder and rectum of all patients considered. In this research work, the amount of dose (Gy) by which an organ at risk absorbed by $2cm^3$ of its volume was taken in order to assess and evaluate the maximum dose (D_{max}) received by the maximum-critical volume of organ at risk (OAR) for all patients. This was done in order to ensure that the dose delivered to the organs at risk (OAR) remain below tolerance levels, reducing the risk of radiation-induced damages. From the table, the mean-absorbed dose for the bladder is 3.40 Gy and for the rectum is 3.07 Gy. The bladder absorbed more mean-dose than the rectum as a result of its proximity with the radiation source.

Table 3: Highest Dose to a $2cm^3$ Volume of the Organs at Risk (BT D_2cc Evaluation)

Patient	Age (Year)	Organs at Risk (OAR)	
		Bladder (Gy)	Rectum (Gy)
P1	38	2.21	2.57
P2	46	5.34	3.17
P3	55	4.47	3.50
P4	25	4.27	2.98
P5	35	2.91	2.51

Patient	Age (Year)	Organs at Risk (OAR)	
		Bladder (Gy)	**Rectum (Gy)**
P6	46	5.76	4.10
P7	39	3.81	3.18
P8	45	3.21	4.11
P9	49	2.61	2.75
P10	35	2.22	3.33
P11	38	4.12	2.15
P12	46	4.44	3.41
P13	41	4.61	4.13
P14	46	4.53	5.11
P15	49	4.12	3.21
P16	35	2.58	2.37
P17	37	2.98	3.24
P18	47	2.65	2.99
P19	41	3.32	3.31
P20	42	3.33	4.11
P21	33	3.78	3.55
P22	48	3.16	3.10
P23	36	3.82	2.10
P24	35	3.21	2.99
P25	38	3.81	2.50
P26	37	3.53	2.21
P27	44	3.59	2.75
P28	43	4.84	2.50
P29	31	4.45	4.25
P30	46	2.84	3.35
P31	31	2.15	3.25
P32	45	2.45	2.91
P33	47	2.38	2.95
P34	36	2.69	3.11
P35	41	2.55	2.25
P36	37	2.59	2.76
P37	49	2.22	2.21
P38	35	2.15	2.76
P39	48	2.33	2.25
P40	41	3.11	2.95
P41	38	3.32	2.91
P42	39	4.21	2.47
P43	45	4.18	3.27
P44	49	3.18	2.91
P45	32	2.95	3.55
Average ± SD	**40.87 ± 6.20**	**3.40 ± 0.90**	**3.07 ± 0.64**

Brachytherapy D_1cc Evaluation for Bladder and Rectum

Table 4 shows the highest dose received to a 1cm^3 (D_1cc) volume of the bladder and rectum of all patients considered. In this research work, the amount of dose (Gy) by which an organ at risk absorbed by 1cm^3 of its volume was delineatef in order to assess and evaluate the average dose (D_{mean}) received by the average-critical volume of organ at risk (OAR) for all patients. This was done in order to ensure that the dose delivered to the organs at risk (OAR) remain within the average safer levels, reducing the risk of radian-induced damages. From the table, the mean-absorbed dose by 1cm^3 of bladder is 3.87 Gy and for rectum is 3.18 Gy. Similar to the dose absorbed by 2cm^3, the bladder received more mean-dose than rectum as a result of its proximity with the radiation source.

Table 4: Highest Dose to a 1cm^3 Volume of the Organs at Risk (BT D_1cc Evaluation)

Patient	Age (Year)	Organs at Risk (OAR)	
		Bladder (Gy)	**Rectum (Gy)**
P1	38	4.90	2.50
P2	46	4.33	3.31
P3	55	3.98	3.48
P4	25	4.11	2.99
P5	35	4.10	3.33

Patient	Age (Year)	Organs at Risk (OAR)	
		Bladder (Gy)	Rectum (Gy)
P6	46	3.78	2.98
P7	39	5.46	4.86
P8	45	5.21	5.11
P9	49	4.89	4.45
P10	35	3.89	4.11
P11	38	3.99	3.56
P12	46	3.45	2.98
P13	41	2.78	2.75
P14	46	2.99	3.56
P15	49	3.92	3.89
P16	35	5.10	4.11
P17	37	4.78	3.79
P18	47	3.98	3.56
P19	41	5.43	3.21
P20	42	2.87	2.99
P21	33	3.78	2.56
P22	48	3.88	2.32
P23	36	3.54	2.11
P24	35	5.11	2.98
P25	38	2.69	2.89
P26	37	2.99	3.21
P27	44	4.11	3.32
P28	43	2.94	2.11
P29	31	2.56	2.98
P30	46	3.97	3.11
P31	31	4.35	3.33
P32	45	3.33	2.22
P33	47	5.11	4.21
P34	36	3.82	2.78
P35	41	4.71	4.32
P36	37	2.86	4.21
P37	49	2.78	3.12
P38	35	3.66	3.19
P39	48	3.78	3.33
P40	41	3.98	2.16
P41	38	3.26	2.19
P42	39	3.77	2.22
P43	45	2.99	2.32
P44	49	2.79	2.31
P45	32	3.30	2.22
Average ± SD	**40.87 ± 6.20**	**3.87 ± 0.80**	**3.18 ± 0.76**

Radiobiological Indices for Target and OAR

Table 5 shows the EQD2-converted values for the parameters gotten from dose-volume histograms (DVHs) extracts of TPS. Radiobiologically, the DVHs dose data are all considered to be physical doses, while the converted values of the DVHs data to EQD2 are all considered to be radiobiological doses. This is because the EQD2 neutralizes dose accumulation from different radiation fractionation scheme (Brachytherapy and EBRT) to 2Gy per fraction, which is vital for radiobiological modeling. As such it is regarded as "Equivalent Dose in 2Gy Fraction" (EQD2). The EQD2-converted mean values were all considered and used for the radiobiological modeling in order to account for dose accumulation from Brachytherapy and External Beam radiotherapy (EBRT) procedures in this research work.

Table 5: EQD2-Converted Mean-Values of Dose-Volume Histograms Parameters

S/N	Structure	Metric	Physical Dose Value (Gy)	EQD2 Value (Gy)
1	HR-CTV	D_{90}	5.78	5.73
2	HR-CTV	D_{98}	6.29	6.33
3	IR-CTV	D_{90}	4.24	3.99
4	IR-CTV	D_{98}	4.62	4.40
5	Bladder	D_{2cc}	3.40	3.00
6	Bladder	D_{1cc}	3.87	3.49

S/N	Structure	Metric	Physical Dose Value (Gy)	EQD2 Value (Gy)
7	Bladder	$D_{0.1}$cc	4.12	3.77
8	Rectum	D_{2}cc	3.07	2.66
9	Rectum	D_{1}cc	3.18	2.77
10	Rectum	$D_{0.1}$cc	3.60	3.21

Figure 6 and 7 presents the numerical output for the radiobiological results of both Tumor Control Probability (TCP) and Normal Tissue Complication Probability (NTCP of the target (tumor) with both bladder and rectum as organs at risk (OAR). For the target (tumor), D_{90} and D_{98} of both HR-CTV and IR-CTV metrics were analyzed and presented for TCP evaluation as shown in Table 6. Similarly, the EQD2 of D_{2}cc of both bladder and rectum were analyzed and presented for NTCP evaluation as shown in Table 7.

Table 6: Tumor Control Probability (TCP) Modeling Result (Tabulated Output)

S/N	Structure	Metrics	TCP (%)
1	HR-CTV	D_{90}	99.97
2	HR-CTV	D_{98}	99.99
3	IR-CTV	D_{90}	85.38
4	IR-CTV	D_{98}	92.04

Table 7: Normal Tissue Complication Probability (NTCP) Result (Tabulated Output)

S/N	Organ at Risk (OAR)	Metrics	NTCP (%)	EQD2 (Gy)	GEC-ESTRO D_{2}cc < 90Gy EQD2 Constraint Result	Comment for Modeling Result
1	Bladder	D_{2}cc	0.00004	56.26	<90Gy EQD2	Below Constraint
2	Rectum	D_{2}cc	0.00004	54.38	<90Gy EQD2	Below Constraint

Pearson Correlational Analysis for
Tumor Control Probability (TCP) vs HR-CTV D_{90}

Figure 1 shows the scatter plot for the correlational analysis between Tumor Control Probability (TCP) and HR-CTV D_{90}. For this correlation, the Pearson value (r) was found to be +0.89 and the statistical significance value (p) was found to be <0.001. From the plot, it is observed that as the dose covering 90% of the HR-CTV increases, the predicted tumor control probability (TCP) increases almost linearly. These results significantly indicates a very strong positive correlation between the TCP and HR-CTV D_{90}. As such, this validates D_{90} as an excellent surrogate marker for treatment efficacy in cervical cancer brachytherapy.

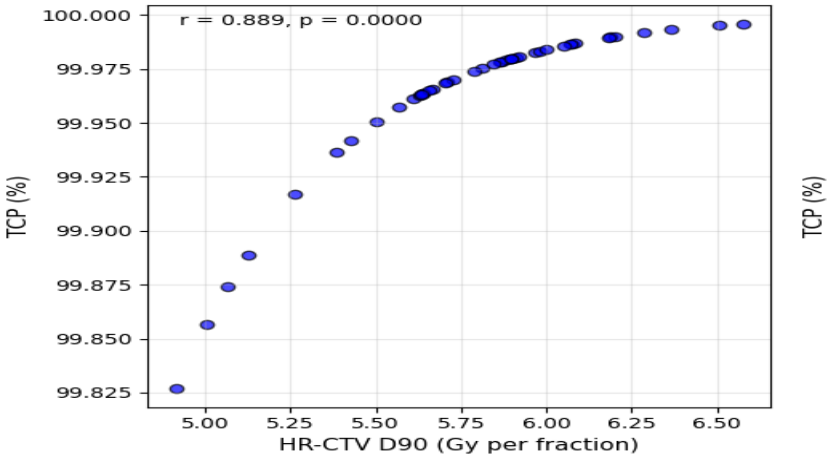


Figure 1: Correlational plot for Tumor Control Probability vs HR-CTV D_{90}

Tumor Control Probability (TCP) vs HR-CTV D_{98}

Figure 2 shows the scatter plot for the correlational analysis between Tumor Control Probability (TCP) and HR-CTV D_{98}. For this correlation, the Pearson value (r) was found to be +0.239 and the statistical significance value (p) was found to be 0.1143. From the plot, it is observed that there is a presence of "shotgun blast" pattern with no clear shape, indicating that the relationship between the TCP and HR-CTV D_{98} is not statistically significant. As such, it confirms that D_{98} is a poor predictor for tumor control in this research work.

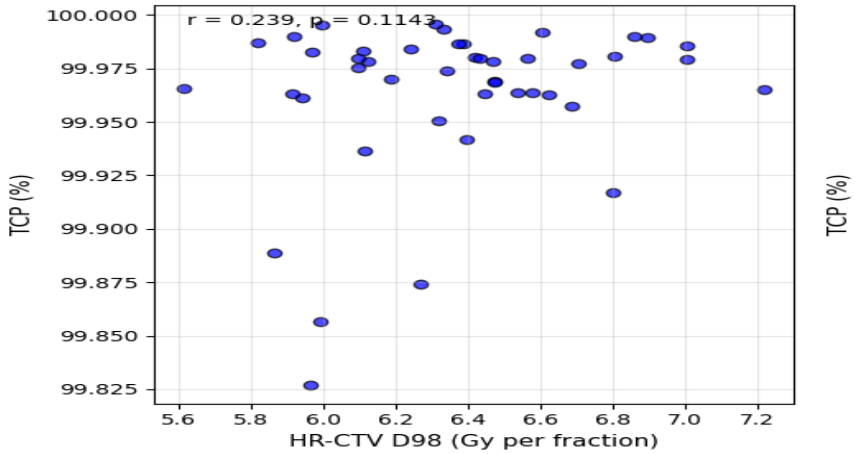


Figure 2: Correlational plot for Tumor Control Probability vs HR-CTV D_{98}

Tumor Control Probability (TCP) vs Total EQD2

Figure 3 shows the scatter plot for the correlational analysis between Tumor Control Probability (TCP) and HR-CTV D_{90} EQD2. For this correlation, the Pearson value (r) was found to be +0.878. From the plot, the curve looks almost identical with the D_{90} correlational plot. This is because the current data of the plot is the EQD2 form of the D_{90} data. This indicates that EQD2 is an excellent summary metric for predicting how likely the tumor is to be eradicated. This plot (r = 0.878) shows that as the HR-CTV D_{90} EQD2 increases, the predicted tumor control probability (TCP) increases. As such, this indicates that there is a significantly strong positive correlation between the tumor control probability (TCP) and HR-CTV D_{90} EQD2.

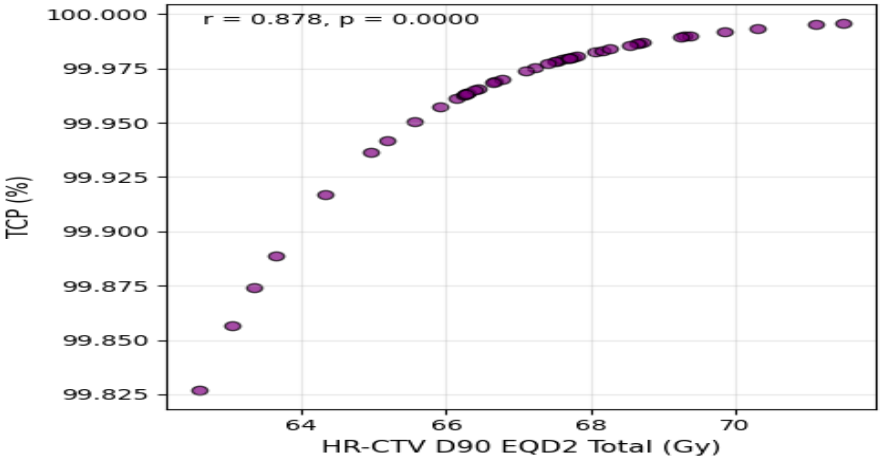


Figure 3: Correlational plot for Tumor Control Probability vs Total EQD2

Normal Tissue Complication Probability (NTCP) vs Bladder D_{2}cc

Figure 4 shows the scatter plot for the correlational analysis between Normal Tissue Complication Probability (NTCP) and Bladder D_{2}cc. For this correlation, the Pearson value (r) was found to be +0.618. From the plot, the trend shows mostly flat at zero, indicating that most patients are in the "safe zone" (0% risk). However, there is a presence of few outliers at the high end, indicating that once the dose exceeds 4.5Gy, the normal tissue complication probability (NTCP) starts to go high. This identifies the "danger threshold" for the bladder. This correlation shows that the probability of having complications to bladder remains at zero level from 1.5Gy to 45Gy. However, as it reaches 4.5Gy, the probability of having complications to bladder increases with a flat trend.

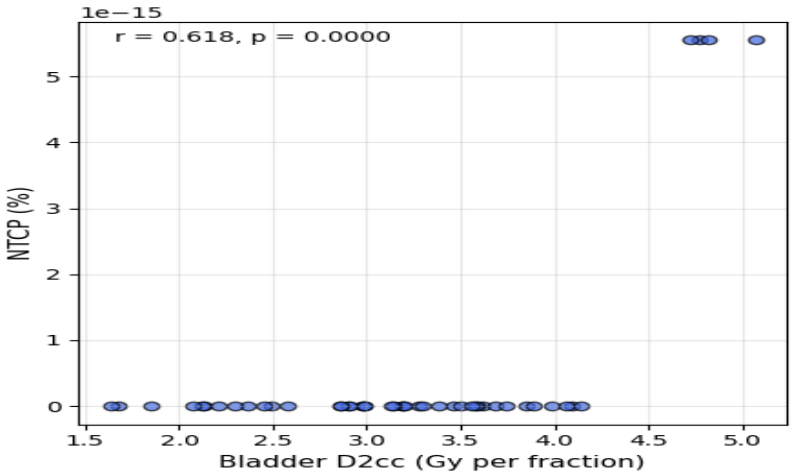


Figure 4: Correlational plot for Normal Tissue Complication Probability vs Bladder D_2cc

Normal Tissue Complication Probability (NTCP) vs Rectum D_2cc

Figure 5 shows the scatter plot for the correlational analysis between Normal Tissue Complication Probability (NTCP) and Rectum D_2cc. For this correlation, the Pearson value (r) was found to be +0.836 with clear exponential growth curve. Unlike the bladder, the rectum shows a much smoother increase in risk as dose increases. This indicates that the rectum is more sensitive to incremental dose than the bladder, making the D_2cc a vital constraint to monitor and avoid rectal toxicity. This implies that the probability of having complications to the rectum increases with increasing dose. As such, the correlation between the normal tissue complication probability (NTCP) and the rectum D_2cc is significantly positive correlation.

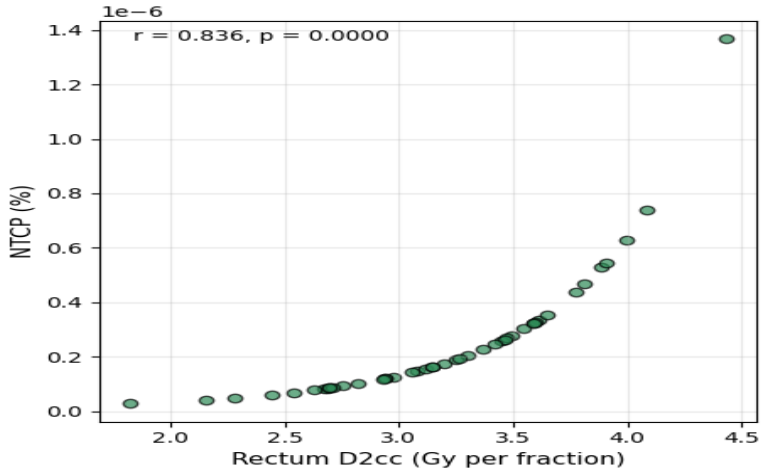


Figure 5: Correlational plot for Normal Tissue Complication Probability vs Rectum D_2cc

Normal Tissue Complication Probability (NTCP) vs Total EQD2

Figure 6 shows the scatter plot for the correlational analysis between Normal Tissue Complication Probability (NTCP) and EQD2 Total. This correlation incorporate the normal tissue complication probability of both bladder and rectum to the EQD2 doses. The plot shows the trend for bladder with blue color, which remains almost entirely at zero level across the same dose range, indicating zero risk as the dose increases between 47.5Gy to 67.5Gy EQD2. For the rectum, it shows a clear sharp increases in risk once the total EQD2 passes 55 Gy to 60Gy. This plot confirms that the rectum is the primary limiting organ for the 45 patients considered in this research work.

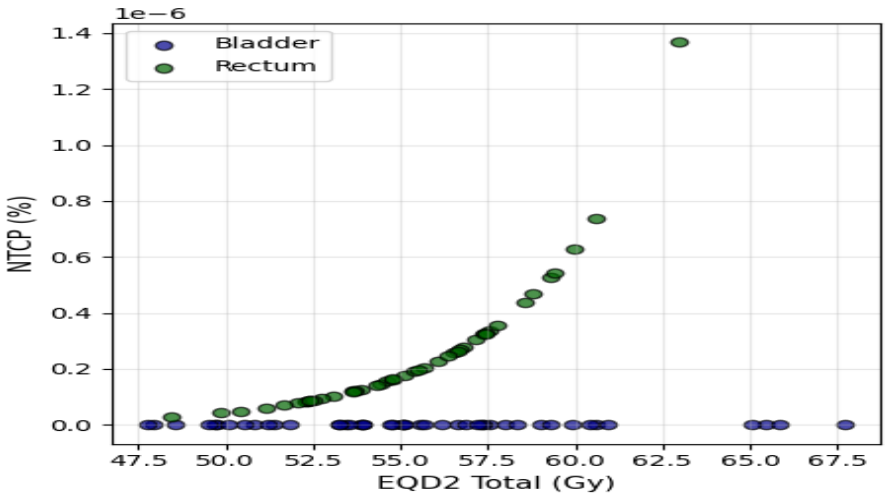


Figure 6: Correlational plot for Normal Tissue Complication Probability vs Total EQD2

Discussion

The Pearson correlation analysis revealed significantly strong and positive relationships between key DVH-metrics and radiobiological indices. The HR-CTV D_{90} and D_{98} showed robust positive correlations with TCP ($r = +0.889$, $p < 0.001$), validating the metrics as reliable surrogate predictors for tumor control. The bladder D_{2cc} demonstrated smooth-average positive correlation with bladder NTCP ($r = 0.618$, $p < 0.001$), indicating that even when D_{2cc} of bladder is increasing, the bladder is safe at the mean-dose level. However, above mean-dose level the probability of complications increases with increasing bladder D_{2cc}. Similarly, the rectum D_{2cc} also showed a strong positive correlation with rectal NTCP ($r = 0.836$, $p < 0.001$). Notably, the rectum D_{2cc} also showed that the rectum is safe even when D_{2cc} increases which exhibited strong and significant correlations with NTCP, supporting the preferential use of D_{2cc} for OAR evaluation in brachytherapy. Overall, this study is totally based on model-predicted biological indices for its outcomes rather than observed clinical outcomes. As such, the model-predicted biological indices validates the clinical use of D_{90} for target evaluation and D_{2cc} for OAR evaluation in cervical cancer brachytherapy, while cautioning against reliance on D_{98} and volumetric parameters as predictors of biological outcome.

Conclusion

This study analyzed the correlation between DVH metrics and radiobiological indices in 45 cervical cancer patients undergoing brachytherapy at National Hospital, Abuja. The results demonstrate that the HR-CTV D_{90} metric, particularly when expressed in EQD2 form, exhibits a strong and statistically significant positive correlation with tumor control probability ($r = +0.889$, $p < 0.001$), confirming its validity as a reliable surrogate marker of treatment efficacy. Conversely, HR-CTV D_{98} showed a weak, non-significant correlation with TCP ($r = +0.239$), indicating that it is a poor predictor of tumor control in this cohort. For organs at risk, the near-maximum dose D_{2cc} proved to be the most informative metric. Rectum D_{2cc} correlated strongly with NTCP ($r = +0.836$), with risk rising sharply beyond approximately 55–60 Gy EQD2, identifying the rectum as the primary dose-limiting organ for these patients. Bladder D_{2cc} correlated moderately ($r = +0.618$), with complication risk remaining negligible up to a threshold of about 4.5 Gy per fraction, beyond which risk increased. In all cases, OAR doses remained well below the GEC-ESTRO D_{2cc} constraint of 90 Gy EQD2, and modeled NTCP values were negligible, confirming that the treatment plans were radiobiologically safe. However, the limitations of this study include a single-center sample of 45 patients, model dependence of TCP/NTCP and absence of longitudinal clinical outcome validation. As such, it is recommended that the use of HR-CTV D_{90} and HR-CTV D_{98} for target assessment of cervical cancer should be prioritized for better and safe tumor eradication. Additionally, future studies could be carried out to validate the associations against actual local control and documented bladder/rectal toxicity in larger multicenter cohorts.

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